

ATTACHMENTS

- Attachment 1 – Conceptual Site Model Topics
 - 1. Basalt Strike and Dip
 - 2. Saprolite Extents
 - 3. Preferential pathways
 - Attachment 1 - Appendix
- Attachment 2 – Interim Groundwater Flow Model
 - 4. Caprock, tuffs, sediments
 - 5. Calibration - Red Hill tunnel inflows
 - 6. Calibration - heads and gradients
 - 7. Coastal submarine boundary
 - Attachment 2 - Appendix
- Attachment 3 – Interim Fate and Transport Analyses
 - 8. Light Non-Aqueous Phase Liquid (LNAPL) Fate and Transport
 - 9. Groundwater Data
 - 10. LNAPL and Dissolved-Phase Plume Distribution
 - Attachment 3 - Appendix
- Attachment 4 – Presentation Slideshow from August, 2018

ATTACHMENT 1

Conceptual Site Model Topics

Item 1. Basalt Strike and Dip

The geometry of lava flows affects the transport of LNAPL, groundwater, and dissolved contaminants. This is particularly true for vadose zone transport of LNAPL. Characterizing the geometry of lava flows – in particular, the predominant strike and dip values and variations about these predominant values – is critical to assessing the risk the Red Hill facility poses to potential groundwater receptors.

The values for the strike and dip of the lava flows reported by consultants to the Navy (CSM Report, page 5-2: *“True dip in the vicinity of Red Hill has been measured at angles of 10–12 degrees, with a strike of 190–205 degrees”*) differ from values that were obtained independently by the regulator SMEs via field observation and measurement and geostatistical analysis of barrel log data, which consistently exhibit lower dip values of about 5 degrees and more westerly strike values (Inset Figure 1.1). Although these differences may appear subtle, they are consequential for groundwater flow and potential contaminant transport paths. This is illustrated in Inset Figure 1.2, which presents pathlines calculated using the interim groundwater model, with values for the direction of anisotropy that differ by 10 degrees (particles depicted in red were computed with a more westerly direction of anisotropy reflecting a more westerly assumed dip direction).

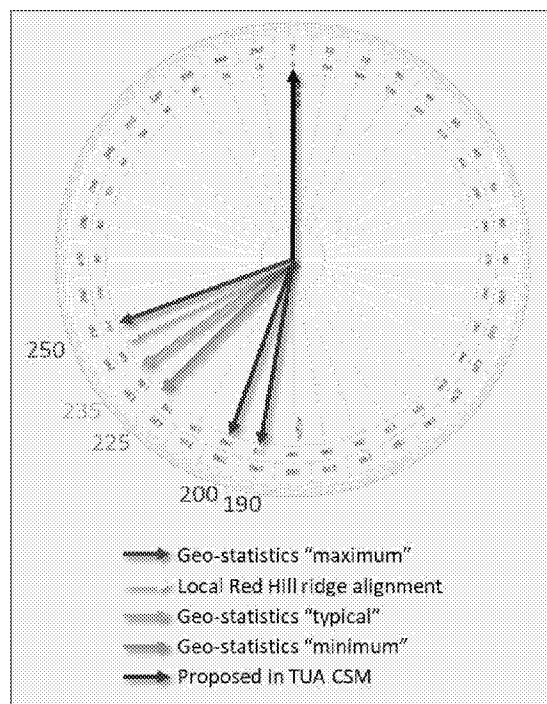


Figure 1.1 Estimated Dip Directions in and Around Red Hill

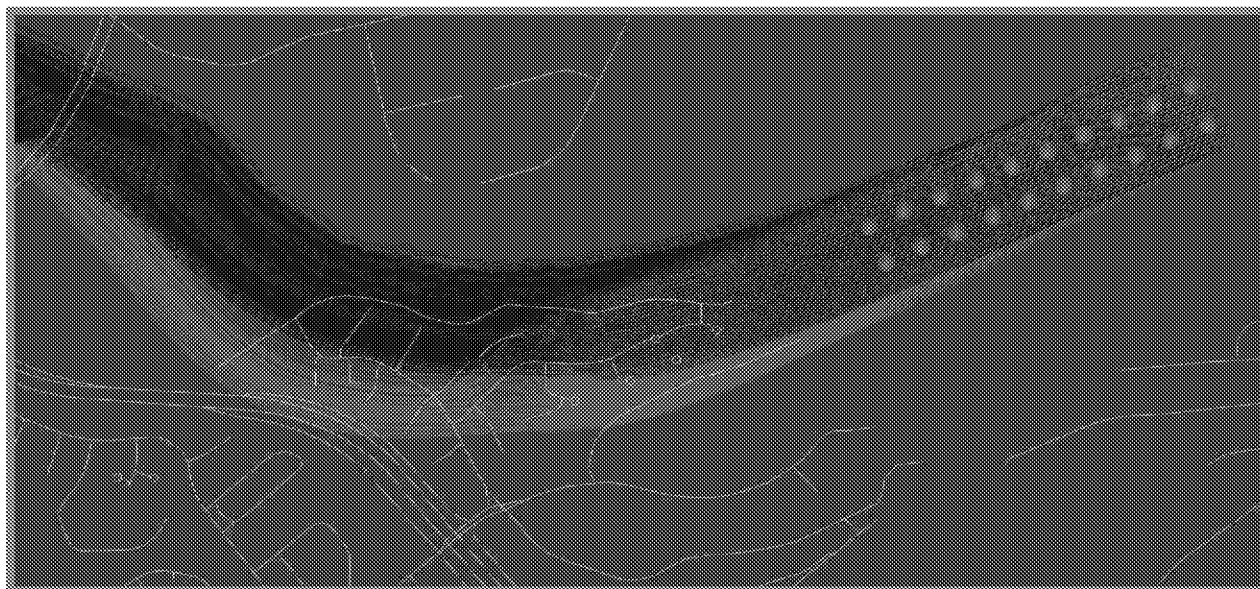


Figure 1.2 Illustration of Particle Path Sensitivity to Assumed Principal (Long-Axis) Direction of Anisotropy

Two difficulties are often encountered obtaining best estimates of dip and strike. First, measurements made at an outcrop face, where the scale is on the order of inches to feet, may not be directly applicable or accurate indicators at the scale over which fluid transport may occur, where distances of hundreds to thousands of feet must be considered. Second, there is likely to be variability in dip and strike values throughout an area, as a function of paleotopography, flow volume, and other factors.

Because there is a variety of data sources for dip and strike at Red Hill, it is appropriate to combine the data while considering their representative scales and quality to obtain a best-estimate at the scale of most interest to the fate-and-transport evaluation. Data sources at Red Hill include (a) close-quarters outcrop measurements such as obtained with a compass-clinometer, (b) surveys of visible outcrop from a distance that allow the geometry of a continuous bed-set to be followed for many tens or hundreds of feet, and (c) geostatistical analysis of the barrel log data. The resulting best-estimate derived from combining these lines of evidence can be to some extent corroborated by intersecting the derived plane with a digital elevation model for comparison with features observed in the field (Inset Figure 1.3).



Figure 1.3 Example of Extensive Correlatable Units Viewed from a Distance using a Theodolite Application for a Camera

References:

Conceptual Site Model, Investigation and Remediation of Releases and Groundwater Protection and Evaluation, Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "CSM Report")

Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "GPEC Report")

Item 2. Saprolite Extents

The saprolite (chemically and physically weathered basalt) is a critical hydrostratigraphic unit (HSU) that affects contaminant transport upon the water table and within groundwater. The saprolite typically exhibits a lower hydraulic conductivity than surrounding basalts and where present beneath the water table, it likely acts as a barrier to contaminant transport, causing groundwater and contaminants to migrate around or beneath it. The depth of the saprolite/basalt interface is important in many areas of the site, but the point up-valley where the saprolite/basalt interface rises above water table is a critical feature in assessing the risk the Red Hill facility poses to drinking water sources.

Review of the representation within the interim groundwater flow model files provided for courtesy review by the Navy of the saprolite/basalt interface depths and general trends (i.e., slopes) relative to the axis of the North and South Halawa Valleys suggests the saprolite is likely deeper down-valley and shallower up-valley than represented in the interim model. One consequence is that the point up-valley where the saprolite/basalt interface rises above water table may be more downslope than currently represented. If this is true, the role of the saprolite as a barrier to flow between valleys – particularly in up-slope areas – may be less protective than the current conceptual model indicates (Inset Figure 2.1).

There are at this time insufficient available data regarding the depth of the saprolite/basalt interface relative to the water table (particularly in North and South Halawa Valleys) to accurately and uniquely represent them in the model. Characterizing the three-dimensional (3D) extent and hydrogeological properties of the saprolite in each valley, including North and South Halawa Valleys, is difficult. Available data include a general CSM regarding basalt weathering and valley infilling; seismic geophysical analysis conducted along several transects; and a single detailed borehole geologic log that crosses the saprolite/basalt interface. Though the seismic data are very informative, ground-truthing is costly and only very localized. Available data from borings – such as the Halawa deep monitoring well – provide specific stratigraphic logs, but even these are accompanied by uncertainty regarding the appropriate depth to pick the interface (inset Figure 2.2). Consequently, uncertainty remains regarding the depth at which to represent the saprolite/basalt interface within North and South Halawa Valleys in particular, and regarding the protection afforded to Halawa Shaft by the saprolites acting as a barrier.

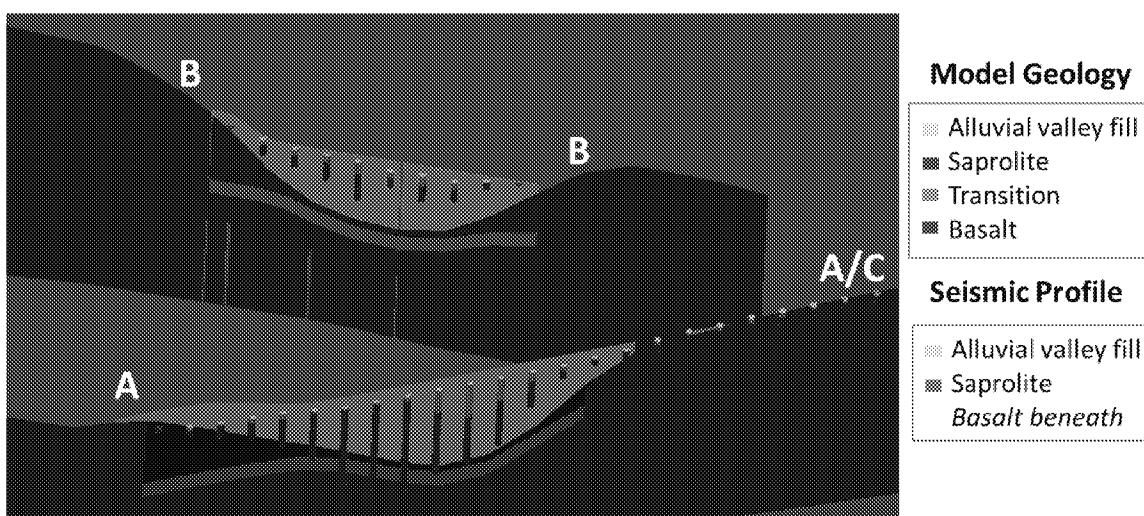


Figure 2.1 Example Comparison of Seismic Profiles and Representation in the Interim Model

Halawa Deep Monitor Well No. 2253-03 Geologic Log by Glenn Bauer	
Depth (ft.)	Description
0-50	Very weathered gray, tan, and red rock; cuttings are rounded and angular
50-70	Same as above, however cuttings are redder and clay present
70-80	Weathered tan cuttings, some of the vesicles lined with Mn
80-100	Weathered reddish-brown friable cuttings
100-110	Same as above, though cuttings are redder
110-130	Weathered tan cuttings
130-140	Weathered red cuttings with clay
140-150	Weathered light brown cuttings
150-170	Weathered brown aa basalt with angular vesicles some coated with Mn
170-180	Weathered dense brown, tan, and gray cuttings
180-190	Mixture of weathered brown pahoehoe and aa basalt
190-210	Weathered gray aa basalt
210-230	Friable brown-gray aa basalt ~-5 ft msl
230-250	Mixture of weathered aa and pahoehoe basalt; some of the pahoehoe has secondary minerals in the vesicles.
250-260	Weathered pahoehoe basalt with secondary minerals in the vesicles
260-270	Mixture of light gray and dark gray aa basalt with a few tachylitic cuttings present
270-280	Weathered gray aa basalt with tachylite
280-290	Dense light gray aa basalt ~-55 ft msl
290-300	Mixture of dense non-vesicular light gray and dark gray aa basalt
300-310	Mixture of weathered gray pahoehoe and non-vesicular aa basalt
310-320	Dense dark gray non-vesicular aa basalt
320-340	Mixture of light and dark gray pahoehoe and aa basalt
340-350	Slightly weathered reddish brown pahoehoe basalt with many small round vesicles

Figure 2.2 Boring Log of Halawa Deep Monitoring Well

Available data which are overwhelmingly large scale and relatively low resolution (i.e., seismic profiles) must be interpreted in the context of the CSM and AOC to provide an appropriate representation for purposes of the flow and transport modeling. The solution to this problem likely lies in two parts: First, re-interpretation of the available data. When the currently seismic-inferred depths to the saprolite/basalt interface are compared to the CSM, the down-valley transects show a deeper interface depth than the current CSM would suggest while the up-valley transects suggest a shallower interface than currently believed. Interpolating between the down-valley and up-valley transects and extrapolating this trend up-slope from the most up-valley transect may help define where the saprolite is no longer beneath the water table and thus a barrier to flow and transport. Second, ground-truthing of the seismic data using test borings (this may already be planned as there is discussion of a test boring adjacent to Seismic Transect E near the Halawa Deep Monitoring Well [HDMW2253-03]). Additional ground-truthing is highly desirable, even though

costly, in targeted areas with maximal information benefit to provide (a) seismic velocities needed to better constrain the depth to the saprolite/basalt reflector and (b) interface elevations at key boring locations to condition the geophysical results.

References:

Conceptual Site Model, Investigation and Remediation of Releases and Groundwater Protection and Evaluation, Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "CSM Report")

Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "GPEC Report")

Item 3. Preferential Pathways.

Voids, fractures, and related features in this shield volcanic setting will potentially allow for rapid transport of both LNAPL and dissolved-phase contaminants. These include lava tubes, bedding plane structures, fractures, etc. While mentioned in the CSM, there is no discussion or quantification of site specific facets. A good framing for hard rock and fractured systems is the ITRC fractured rock CSM schematic (e.g., Figure 3.1). Some of the more important factors are the orientation of these features, the wall roughness, dip, aperture ranges, continuity and density. While some of these aspects have been discussed in the CSM, none have been quantified (excepting dip, around which there are remaining questions), which would directly assist in considerations of contaminant F&T, particularly the LNAPL migration. For instance, based on the geologic barrel logging when the Red Hill tanks were installed, lava tubes are present beneath 13 of the 20 tanks; Tanks 1, 3, 4, 6, 8, 9, 13, 15, 16, 17, 18, 19, and 20. Lava tubes are expected to be a smooth-walled and distally continuous features (personal comm, Dr. Scott Rowland, U.H., 2018) that if intersected by LNAPL in the unsaturated zone would act as essentially an open-pipe transport conduits. In-filling, collapse and other post-deposition factors can affect how these conduits might behave, as noted in the Navy CSM. However, there is no site or area specific characterization of these important transport features in the CSM, absent which, little can be inferred regarding their potential effects on transport.

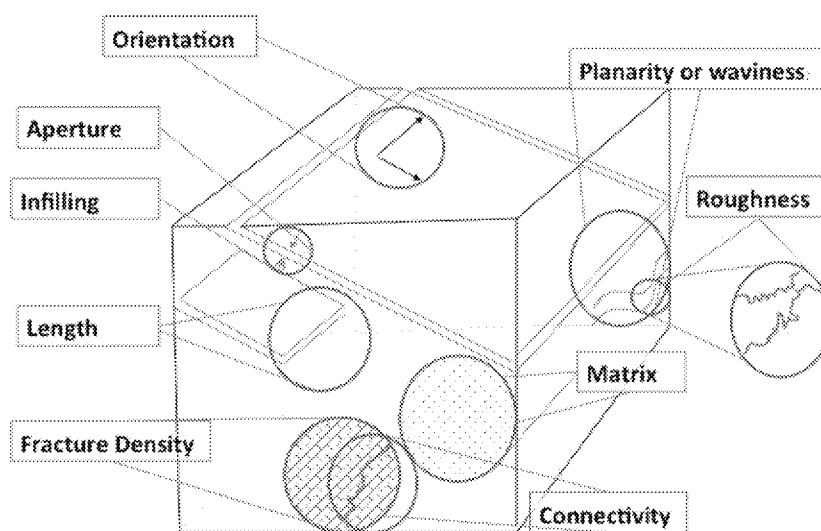


Figure 3.1 Key fracture/hard rock characteristics as defined by the Interstate Technology Regulatory Council (ITRC, December 2017). Of those shown, the most important factors are the orientation of these features, the wall roughness, dip, aperture ranges, continuity and feature density.

A portion of this issue is discussed in the bedding strike and dip discussion above. Based on the range of dip measurements by both the Navy and HDOH scientists, it is clear that there is significant variability in the dip and its azimuth. It also appears that there are changes in dip from the axis of the Red Hill Ridge to outlying areas. The Navy team does some good work in drawing analogies between current volcanic activity on the Big Island and past processes at work on O'ahu. We would simply note that on the Big

recognized field methods. Transport estimates, which are the backbone of risk evaluations will be much more reliable when coupled with these types of site specific observational data.

References:

API #4731, 2003. *Light Non-Aqueous Phase Liquid (LNAPL) Parameters Database - Version 2.0 - User Guide*.

Conceptual Site Model, Investigation and Remediation of Releases and Groundwater Protection and Evaluation, Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "CSM Report")

Fractured Bedrock Field Methods and Tools: Volume I, Main Report. Science Advisory Board for Contaminated Sites in British Columbia, authored by Golder & Associates, 2010.

Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "GPEC Report").

Hydrogeologic characterization of fractured rock masses intended for disposal of radioactive waste
DM Reeves, R Parashar, Y Zhang - *Radioactive Waste*, 2012.

Huyakorn, P.S., Panday, S., Wu, Y.S., 1994. A Three Dimensional Multiphase Flow Model for Assessing NAPL Contamination in Porous and Fractured Media, 1. Formulation. *Journal of Contaminant Hydrology*, #16 (1994), pp 109-130.

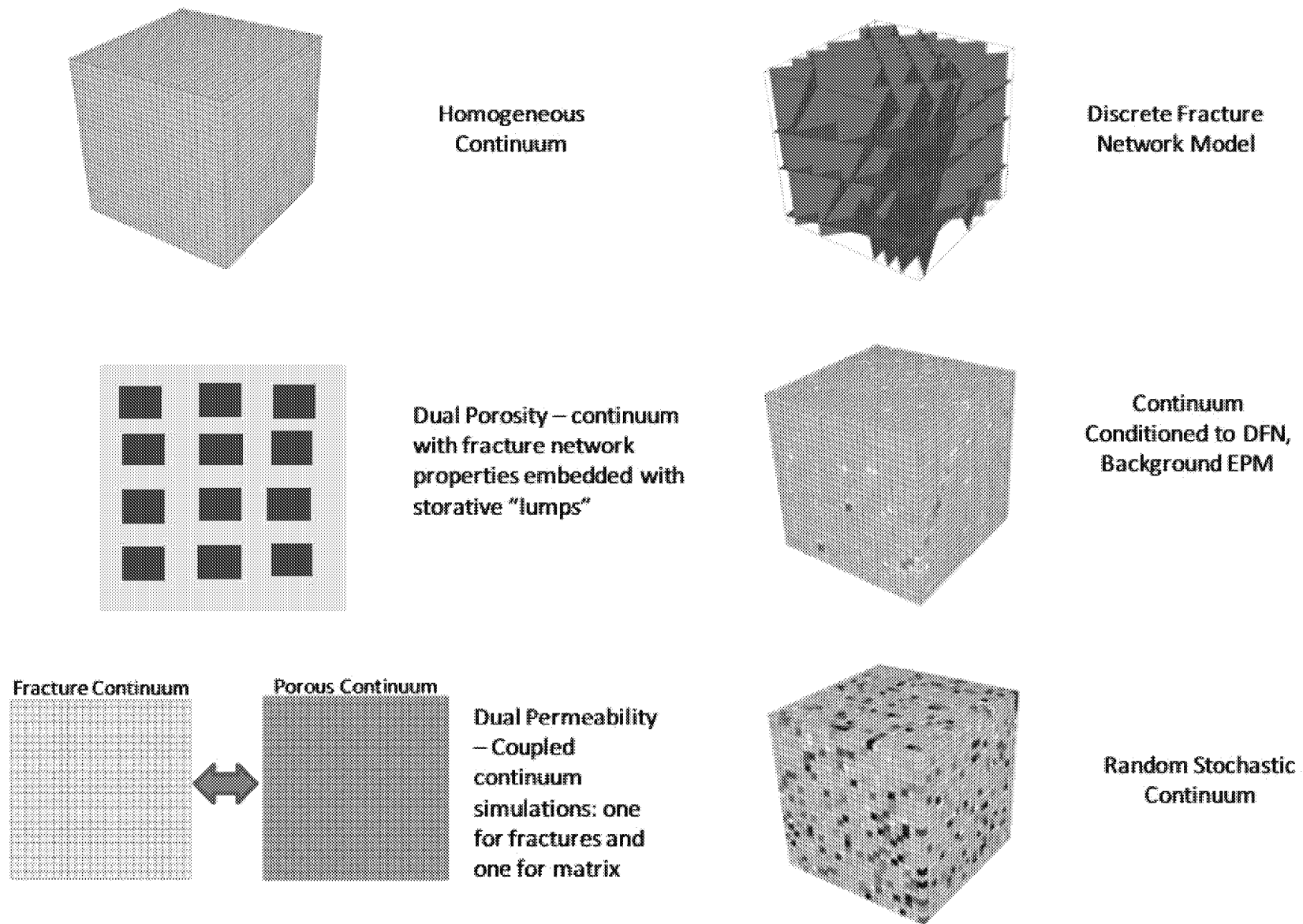
Characterization and Remediation in Fractured Rocks. Online publication: <https://fracturedrx-1.itrcweb.org/> ITRC, 2017.

Neuman, S. P., 2005. Trends, Prospects and Challenges In Quantifying Flow And Transport Through Fractured Rocks. *Hydrogeology Journal*, March 2005, Volume 13, Issue 1, pp 124–147.

Attachment 1 - Appendix

Figure 3. Representations of fractured media.

For Red Hill, the CSM would benefit by conceptualizing and quantifying key systemic features and their potential behavioral characteristics, as well as deciding on the transport framework that is most representative.



(source: Fractured Bedrock Field Methods and Analytical Tools, Volume 1, Main Report, Submitted to the Ministry of Environment Canada, April 2010.

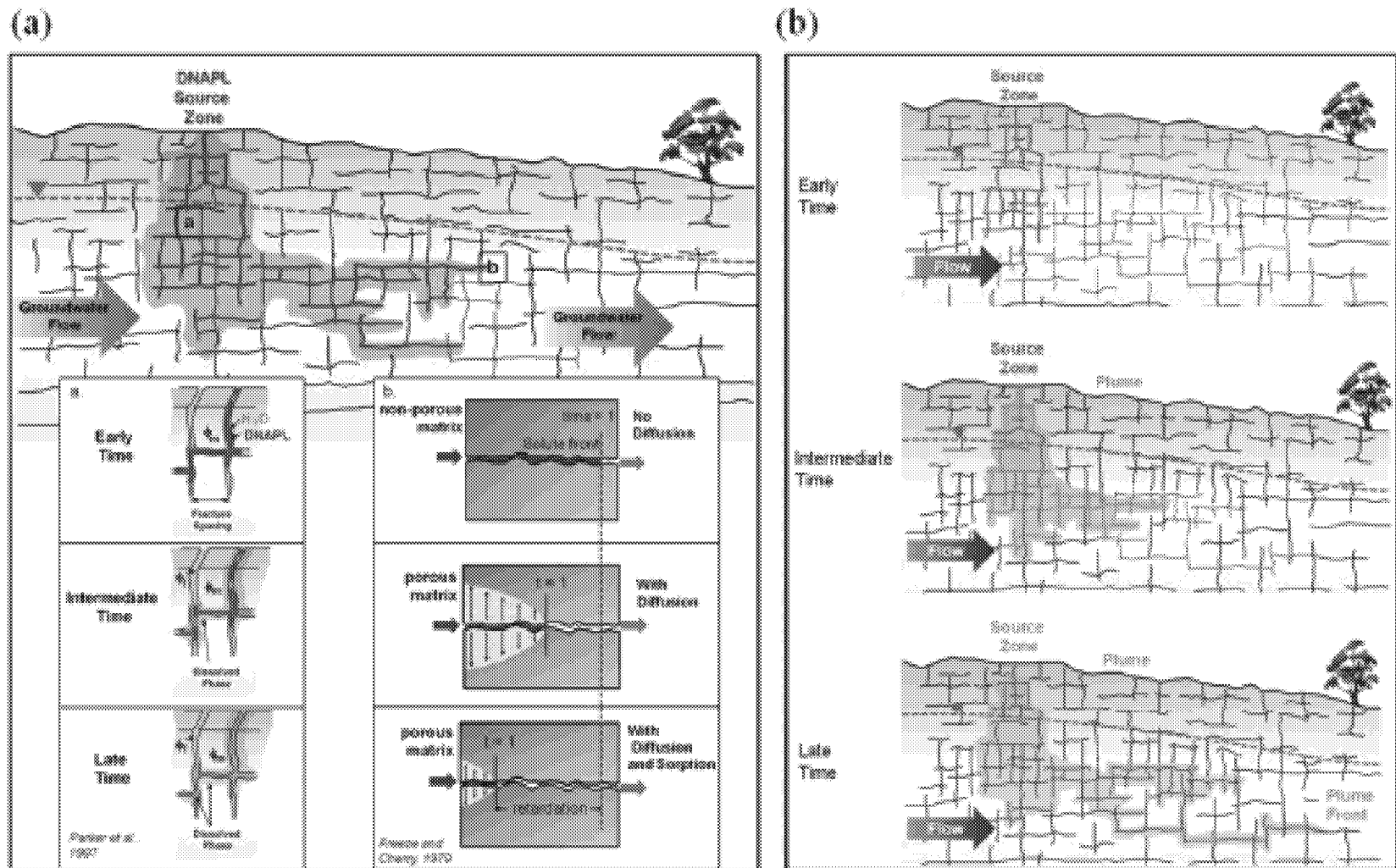
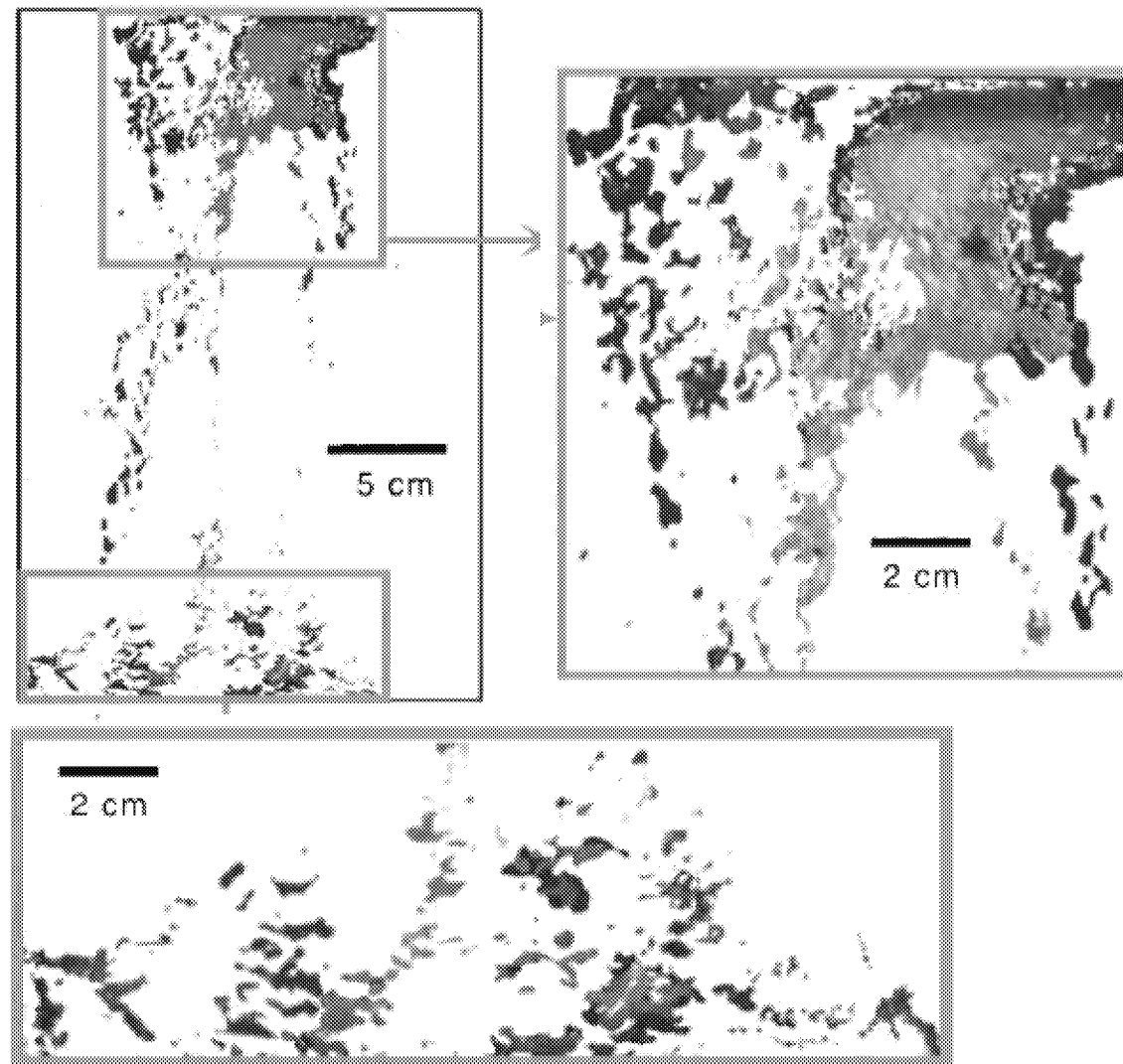


Fig. 1: Conceptualization of source zone and plume evolution in fractured sedimentary rock: (a) schematic cross-section showing DNAPL release with formation of a downgradient plume, with insets showing source zone evolution (adapted from Parker et al., 1997) and diffusion effects on contaminant migration (adapted from Freeze and Cherry, 1979), and (b) conceptual stages of source zone and plume evolution (adapted from Parker et al., 2010).

Similar to the Hunt (1996) lithologic schematic, these authors discuss the quantification of such a network for the purposes of understanding the nature of contaminant F&T. The features of Hunt's model need to be bounded by quantifying the various parametric aspects of those features and their impact on transport.

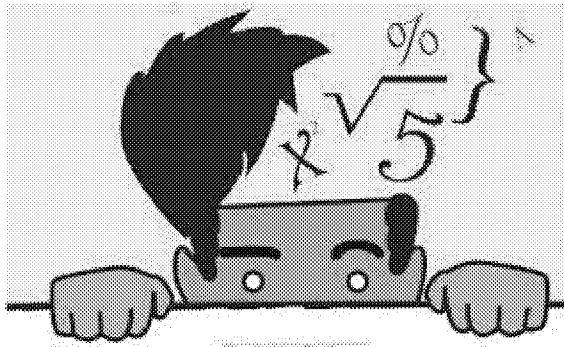
NAPL Distribution in a Fracture



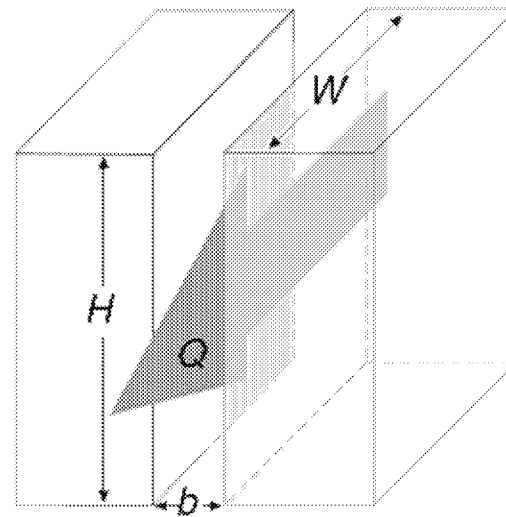
Geller et al., 2000

Heterogeneity of transport is the expected norm in a fractured/hard rock system such as Red Hill and the complexity of the LNAPL CSM needs to comport with the actual complexity of the system.

Just a Little Math... Cubic & Quintic Flow



For “simple” fractures



$$Q = -\frac{\rho g}{12\mu} b^3 \partial h$$

$$K = \frac{2b^2 \rho g}{12\mu}$$

Holy exponential cow!

Suggested for “real” fractures with aperture/length correlations

$$Q = -\frac{4\rho g}{3\mu(\pi\alpha)^2} b^5 \partial h$$

after Climczak et al., 2009

From a transport quantification point of view, fractures and voids of larger apertures and connectivity will allow for very rapid transport of LNAPL. These features need to be understood and quantified so the implications for transport may be understood and constrained.

ATTACHMENT 2

Interim Groundwater Flow Model

Item 4. Caprock, Tuffs and Sediments

The CSM that underlies the interim and final numerical groundwater and LNAPL models needs to represent, albeit in an approximate manner, the principle features and processes that affect groundwater flow and contaminant migration. The configuration and properties of the caprock, tuffs and sediments are collectively an important feature of the hydrogeologic system. The interim groundwater model terminates the saprolites a short distance down-valley of Red Hill; represents the caprock as a wide-reaching uniform and continuous layer; and does not appear to represent older Honolulu volcanics or surrounding finer sediments. These areas were evaporative “lakes” at one time, exhibiting strongly artesian fresh-water conditions, and they may form a barrier to flow influencing groundwater flow and contaminant transport.

Gradients simulated by the interim flow model, as presented in the GPEC Report and determined from the interim model files provided for courtesy review by the Navy, do not comport well with gradients determined from synoptic data in and around Red Hill facility. While this is in part related to conditions local to Red Hill, analyses conducted using the interim model exhibit high sensitivity to conditions downgradient of Red Hill - specifically, in the area broadly represented by the caprock (GPEC Report Section 5.9). This suggests that although uncertain, because there are insufficient data available to uniquely and accurately specify the distribution and properties of downgradient geologic units, it is important to represent the hydrostratigraphy downgradient of the Red Hill facility as accurately as possible, using as one basis the overarching CSM regarding the distribution and properties of these features (Inset Figure 3.1).

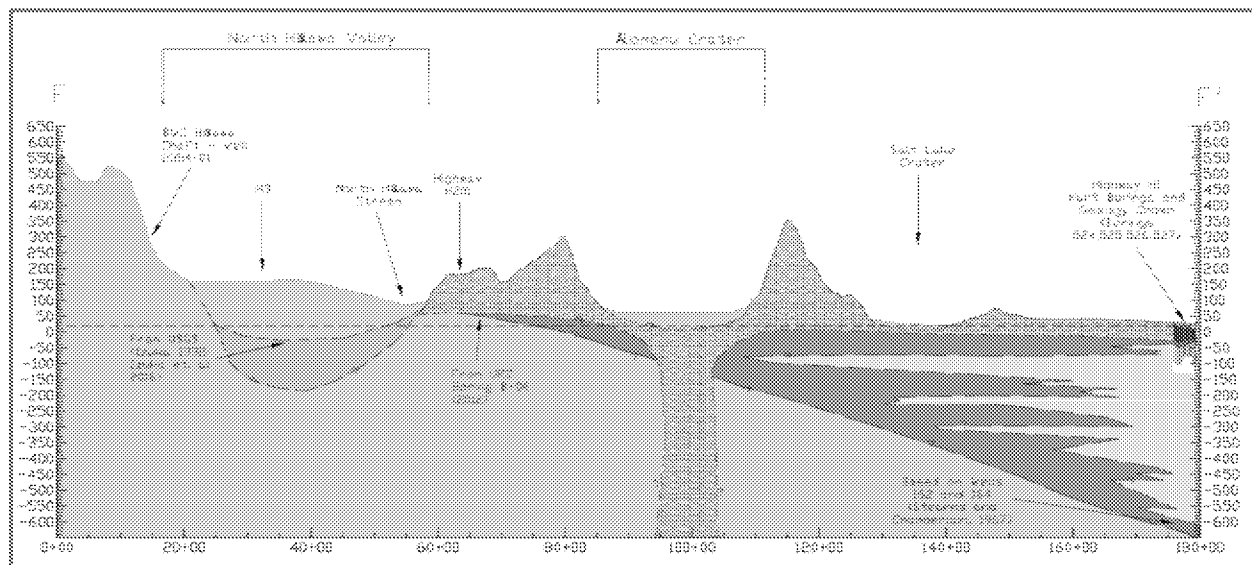


Figure 3.1 Example Figure Illustrating Hydrostratigraphic Features

Available information must be interpreted in the context of the CSM and AOC to provide an appropriate representation for flow and transport modeling. The solution to this problem likely lies in two parts: First, re-interpretation of the available data, and expanded use of sensitivity analysis and model calibration to help identify probable geometries and properties, including for example extending the saprolites down-valley, and differentiating Honolulu volcanics from surrounding sediments. Second, based on the anticipated results of sensitivity analyses conducted with this updated representation of

these features, consideration should be given to methods of data collection to better constrain the likely presence, extent and properties of these features. For example, other sources of information and data collection – such as airborne gravity surveys – may provide further evidence for the extents of some of these features.

References:

Conceptual Site Model, Investigation and Remediation of Releases and Groundwater Protection and Evaluation, Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: “CSM Report”)

Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: “GPEC Report”)

Item 5. Calibration – Tunnel Inflows

The role of Red Hill shaft as a mitigating hydraulic containment measure in the event of a contaminant release depends on its ability to develop a capture zone that encompasses the area impacted by a release. As a Hawaii-style water supply, Red Hill shaft does not function as a simple vertical well: it gains water via seepage along the quasi-horizontal tunnel that extends broadly eastward from the vertical shaft. One role of the interim and final groundwater models is to demonstrate the likely extent of capture (zone of contribution) of Red Hill shaft under a range of plausible conditions.

The interim groundwater flow model does represent Red Hill shaft as a linear quasi-horizontal feature rather than at a single vertical point, which is appropriate. However, the distribution of inflows to the eastern tunnel extension simulated by the interim model as determined from the model files provided for courtesy review by the Navy does not appear to match the inflow pattern encountered during tunnel construction (Inset Figure 5.1). During construction, a clinker zone was encountered that contributed more than 60% of the flow to the tunnel whereas the interim model simulates uniform inflow along the tunnel. This difference highlights two issues: first, there is heterogeneity present on a scale of many tens

to hundreds of feet that is not well understood nor represented in the interim model; second, the extent of capture developed by the tunnel may be more head-dependent than represented in the interim model. That is, the capture zone under high water level conditions may be dominated by seepage from this clinker at the end of the east tunnel, but under low water level conditions may be dominated by drawdown within the vertical shaft itself. Sensitivity analyses conducted with the interim model indicate that the model exhibits sensitivity to the potential presence of a clinker zone (GPEC Report Section 5.9).

The presence of large-scale heterogeneity is documented: however, the distribution and properties of these heterogeneities are not well known and cannot be perfectly represented in models. Despite this, consideration must be given to the role they may play in the

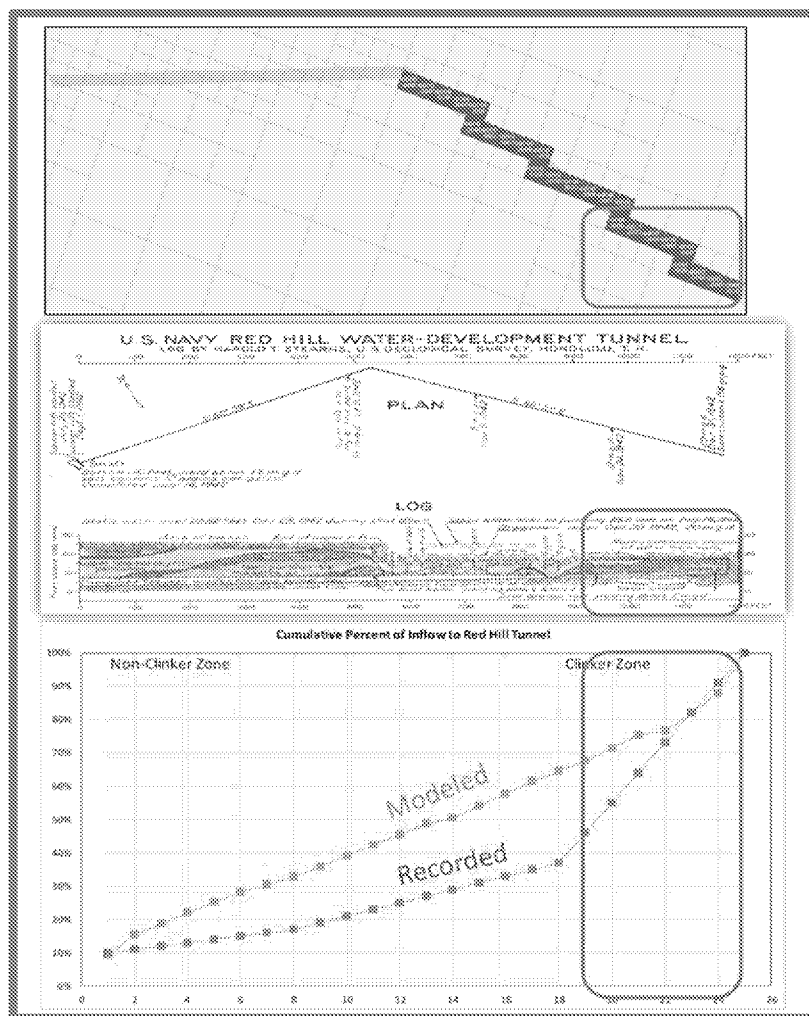


Figure 5.1 Schematic of Recorded and Simulated Inflows

calibration of the groundwater model, and any inability to reasonably match heads and gradients; the zone of contribution to Red Hill shaft and tunnel system under different conditions; and, the transport and fate of constituents in groundwater.

The final CSM and model should make a greater effort to evaluate the possible role of these heterogeneities – in particular, as an illustrative example, the Red Hill tunnel clinker – on calibration, zones of contribution, and contaminant transport. This may be accomplished for example by evaluating the zone of contribution under high water level conditions dominated by tunnel seepage, and under low water level conditions dominated by active pumping at the Red Hill shaft.

References:

Conceptual Site Model, Investigation and Remediation of Releases and Groundwater Protection and Evaluation, Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: “CSM Report”)

Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: “GPEC Report”)

Item 6. Calibration Heads and Gradients

Groundwater flow and contaminant migration are, under most circumstances, determined or strongly influenced by hydraulic gradients. A groundwater model developed to predict the transport and fate of contaminants from a release should present reasonable correspondence with hydraulic gradients determined using site-specific measurements, to provide confidence the model will reasonably predict contaminant transport.

Hydraulic gradients determined from measured data are generally flat in and around Red Hill. On most occasions, gradients are to the southwest at a low slope, but occasionally they appear to be to the northwest and possibly north. The interim model outputs presented in the GPEC Report do not closely reproduce the magnitude or direction of these gradients. Flow in the calibrated interim model is dominantly Mauka-to-Makai, and most of the sensitivity-derived alternative models demonstrate flow toward Red Hill shaft at gradients that are 10 to 100 times higher than measured values. Although the sensitivity analyses do present a range of simulated gradients (GPEC Report Section 5.9), the distribution of simulated gradients across all models that were provided for courtesy review by the Navy does not match closely values derived from the synoptic data (Inset Figure 6.1).

Historical data had shortcomings (frequency, reference elevations, lack of pumping knowledge) that they were not easily amenable to rigorous analysis. Recent synoptic data provide improved frequency and quality. These data suggest that certain aspects of the CSM incorporated into the interim flow model may prevent the model from reproducing these gradients, including the saprolite distribution; basalt strike and dip; the “keying” of saprolites into down-valley Honolulu volcanics, older sediments and cap rock; and recharge distribution and rates.

The final CSM and model should focus on analyzing recent high-quality synoptic data to the extent possible, and down-weight analyses based on older data. Despite difficulties preparing water level maps, pairwise head-difference plots can show the effects of pumping on gradients and the frequency and magnitude of gradient reversals. Steady-state model calibration should focus on demonstrating a match

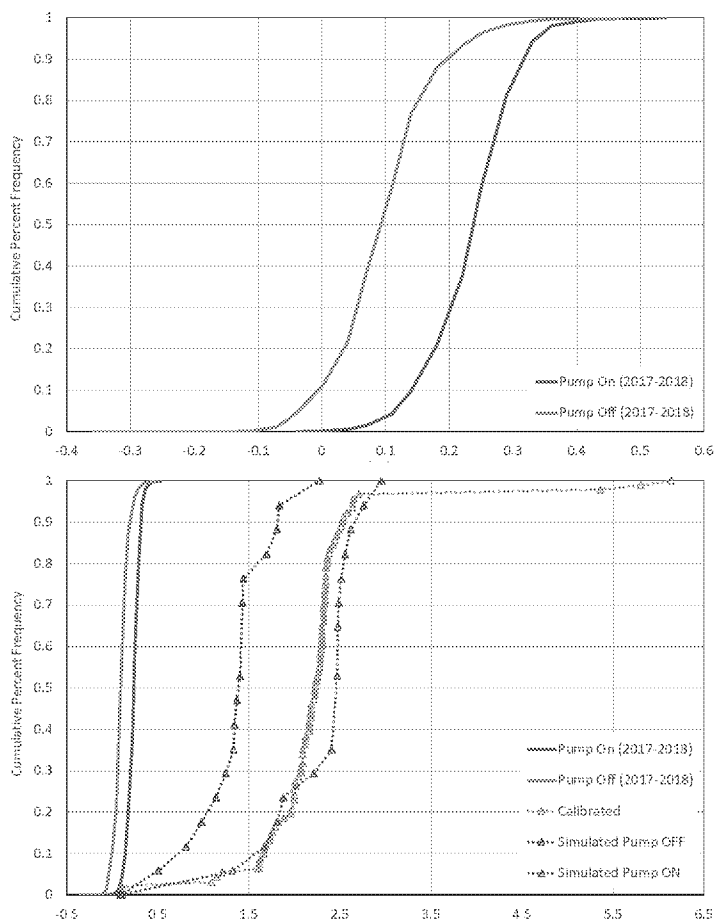


Figure 6.1 Example Comparison of Pairwise Head Differences from Synoptic Data with Simulate Head Differences from All Interim Models

with regional patterns and with representative local gradients under pumping and non-pumping conditions. This combination is required to demonstrate that the model is useful for near-field transport to understand the available groundwater data, and for developing predictions of capture zones for Red Hill shaft and Halawa shaft to help evaluate risk and mitigating responses or strategies. Transient calibration will provide information on T, S, anisotropy, and possibly on the geometry of features such as the saprolite but is not a substitute for obtaining reasonable mean-centered correspondence to the measured gradients (or pairwise head differences).

References:

Conceptual Site Model, Investigation and Remediation of Releases and Groundwater Protection and Evaluation, Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "CSM Report")

Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "GPEC Report")

Item 7. Coastal Submarine Discharge

The CSM that underlies the interim numerical groundwater and LNAPL models and will underlie the final versions needs to represent the principle features and processes that affect groundwater flow and contaminant migration. There is uncertainty regarding the downgradient outflow boundary, which as currently represented in the model may lead to a bias toward discharge occurring in the northeast Pearl Harbor area. All groundwater that is not extracted by wells or discharged to streams or springs flows to the saline water bodies: how the model distributes groundwater between the Pearl Harbor Estuary and offshore (submarine) discharge areas can affect upslope flow patterns including the Red Hill area.

Gradients simulated by the interim flow model do not comport well with measured gradients in and around Red Hill facility. While this is in part related to conditions local to Red Hill, the interim model exhibit high sensitivity to conditions downgradient of Red Hill. The interim model represents the downgradient discharge (outflow) from the model to the saline water bodies (Pearl Harbor Estuary and offshore areas south of Pearl Harbor) via a general head boundary (GHB) with some areas exhibiting intervening high-conductivity cap rock (GPEC Report Section 4.4). The GHB allows flow based upon an ascribed elevation and an intervening resistance between the boundary and the aquifer. In this configuration, groundwater is simulated to preferentially flow to the eastern part of Pearl Harbor Estuary. However, muds and volcanic ash on the bottom of Pearl Harbor may impede flow leading to more flow from Moanalua Aquifer to the Waimalu Aquifer. Flow from the Moanalua Aquifer to the Waimalu Aquifer where spring systems and large pumping centers create significant drawdown could result in a flow path beneath the Red Hill facility to the northwest.

Thus, though there are insufficient available data regarding the distribution and properties of downgradient discharge outflow boundary to accurately and uniquely represent it in the groundwater model, sensitivity analyses indicate this area is important to regional flow patterns (GPEC Report Section 5.9). Therefore, available information must be interpreted in the context of the CSM and

AOC to provide an appropriate representation for purposes of the flow and transport modeling.

The approach to simulating the groundwater flow to the Pearl Harbor Estuary and the southern offshore regions needs further work. Although uncertain in extent and character, it is important to represent the downgradient outflow conditions as accurately as possible, using as one basis the CSM regarding the distribution and properties of these features, and also other sources of information (Inset Figure 10.1).

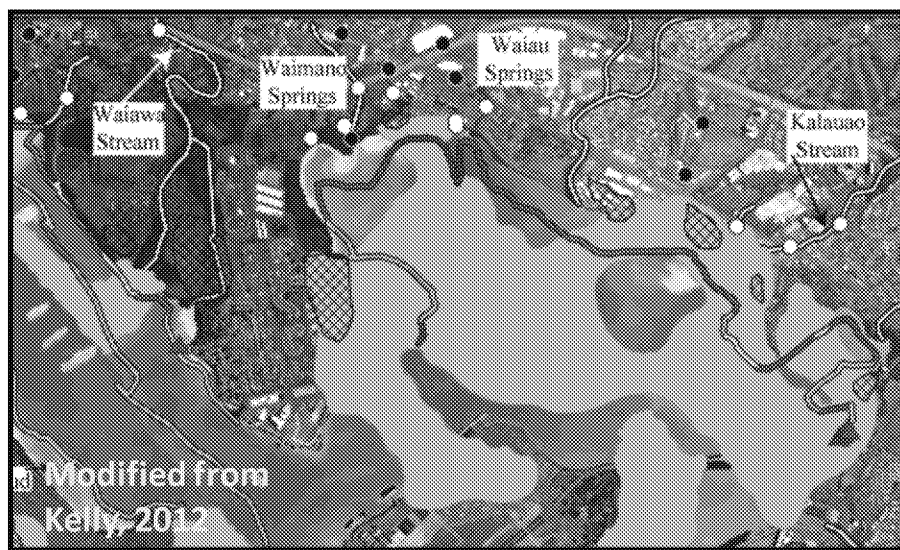


Figure 10.1 Example Figure Illustrating Variable Discharge to Pearl Harbor

The solution likely lies in two parts: First, re-interpretation of the available data, with expanded use of sensitivity analysis and model calibration to help identify probable geometries and properties. Model refinements may include using multiple layers to simulate the caprock and include older alluvial sediments and the muds and tuffs that blanket the floor of Pearl Harbor. Second, based on the anticipated results of sensitivity analyses conducted with this updated representation of these features, consideration should be given to methods of data collection to better constrain the likely presence, extent and properties of these features.

References:

Conceptual Site Model, Investigation and Remediation of Releases and Groundwater Protection and Evaluation, Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "CSM Report")

Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "GPEC Report")

Attachment 2 – Appendix

ATTACHMENT 3

Interim Fate and Transport Analyses

ITEM 8. LNAPL Fate and Transport.

It is unclear in the CSM how the LNAPL transport will be modeled “..to estimate LNAPL migration for current and potential future releases, including the fraction expected to be immobilized in the vadose zone, and the fraction expected to reach groundwater. The modeling effort will also include an assessment of the potential migration of LNAPL within the saturated zone.” Based on prior CSM presentations by the Navy team and limited discussion in the CSM, the primary component of the LNAPL modeling is a “statistical LNAPL holding model” that accounts for only the residualization of some fraction of an assumed LNAPL release within an assumed release geometry. That is augmented in the groundwater zone by assuming distributions of LNAPL source materials in the aquifer that then feed dissolved-phase fluxes with no active LNAPL transport calculations. While perhaps useful for some general framing, this non-dynamic form of LNAPL modeling cannot determine critical aspects of risk determinations and potential mitigation approaches. Some key regulatory questions for the linked dynamic LNAPL and groundwater transport models are:

- What range of LNAPL releases might reach groundwater as a function of release rates, locations, fuel types, and other characteristics? Transport in each area of the tank farm can reasonably be expected to behave differently based on the boring and barrel logging of the ridge. How do geologic distribution differences affect the transport outcomes?
- How do chronic low-rate releases behave in comparison to large-scale sudden events? How can the release event ranges be confidently bracketed?
- Related, what is the fraction of residual capacity already uptaken by pre-existing releases and how can that be determined from existing data? If it cannot be determined from existing data, what conservative assumptions might be made?
- How fast and how far might LNAPL travel as a function of various release scenarios and in what directions? The approach discussed by the Navy team assumes a direction (SW) of LNAPL transport that does not comport with the observed plume transport discussed above.
- Given the noted potential for past northwesterly transport, can hydraulic capture be achieved for LNAPL containment in context with the estimated LNAPL transport rates and under what kinds of pumping regimes?
- How far would an LNAPL release need to propagate to create potential detections at the Halawa Shaft and/or other groundwater resource areas and with what release volume and scenario could that occur?

Screening LNAPL transport work by the regulatory SMEs indicates that an LNAPL release of sufficient volume will reach the water table and the lateral propagation will be rapid (Appendix). A release that exceeds the residualization capacity of the formation could reach the water table zone in less than 7 days and propagate to ~ 250-ft distance in that time, and more than 500-ft in less than 30 days. Again, these are just screening transport estimates that consider primary transient mechanisms, but they do indicate the potential for rapid rates and distances of LNAPL transport under certain conditions. This is particularly true for scenarios that exceed the residualization capacity of the formation, which is presently undefined in the CSM or by any correlative data. Outcomes much different than these examples are of course possible within the various assumptions that might currently be made, which is why a more robust and dynamic LNAPL F&T program is recommended in CSM updates. Our collective

questions revolve around transient aspects of transport, risk and mitigation; the estimation approach needs to do the same and parallel the thinking that has gone into the numerical groundwater model where understanding transient aspects is also important.

In part, the rapid transport indicated in the scenarios above is because of the large pressure heads that can be generated both by the size of the USTs and their elevation above the water table. These large potential LNAPL gradients vastly exceed the very shallow groundwater gradients in the area and LNAPL transport will not likely be strongly influenced by those. Modeling is the usual method by which these types of transient processes can be identified and assessed, particularly when site specific data are sparse around the release source area.

With regard to the many assumptions about the outcome of the 2014 Tank 5 release, perhaps one of the most fundamental is the estimated release volume of 27,000 gallons. The regulatory SMEs have not been able to find the specific release volume calculations nor the certainty bounds on that value. In our experience, release volume estimates have uncertainty that would affect the assumptions and conclusions in the CSM, particularly given that the release occurred during both filling and draining of Tank 5. We believe the particular details of the release estimate need to be fully detailed in the CSM and the implications of that range considered in the evaluations.

With regard to LNAPL transport parameterization, the agencies recognize the challenges in such characterization. However, the limitations of core-scale testing in petrophysical labs (CSM Chapter 5.2.3) is generally well-known and already demonstrated through Red Hill data where laboratory-derived permeability data are orders of magnitude smaller than field-scale. Further, the capillary centrifuge testing has also been shown to be suspect through the results of the API LNAPL Parameters Database compilation (API 4731, 2006), where residual saturation is over-estimated as compared to field studies and other soil properties databases (e.g. U.S. Salinity Lab and others). It has also been observed in work at the IDPP OU1-C area in Honolulu that the residual saturations determined in the lab are unreliable and non-conservative. Briefly, in situ samples collected from the free-phase LNAPL zone guided by continuous coring generally tested at or below residual saturation values in site areas of significant free product LNAPL. Since LNAPL cannot flow into a well if it is below residual in the formation, these lab-derived values conflict with site LNAPL observations; these example lab tests are the same methods discussed by the Navy team. The same limitations may be expected for the Red Hill petrophysical testing program and we recommend the Navy team develop alternate bench and field testing and data collection methods to more realistically constrain these important LNAPL F&T parameters. Dynamic model calibration is a related method of parameterization support, and transient vapor probe data are a potential calibration data set. Regardless, absent additional source zone characterization data, the LNAPL residual capacity will remain unconstrained along with other important elements to the LNAPL transport regime. As noted, this is one of several critical factors in the dynamic evaluation of LNAPL transport and potential risks to the groundwater system. Where measurements and data are absent, a greater degree of conservatism in the estimation approaches is necessary to allow for that uncertainty.

References:

API #4731, 2003. *Light Non-Aqueous Phase Liquid (LNAPL) Parameters Database - Version 2.0 - User Guide*.

Conceptual Site Model, Investigation and Remediation of Releases and Groundwater Protection and Evaluation, Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "CSM Report")

Fractured Bedrock Field Methods and Tools: Volume I, Main Report. Science Advisory Board for Contaminated Sites in British Columbia, authored by Golder & Associates, 2010.

Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "GPEC Report").

Hydrogeologic characterization of fractured rock masses intended for disposal of radioactive waste
DM Reeves, R Parashar, Y Zhang - *Radioactive Waste*, 2012.

Huyakorn, P.S., Panday, S., Wu, Y.S., 1994. A Three Dimensional Multiphase Flow Model for Assessing NAPL Contamination in Porous and Fractured Media, 1. Formulation. *Journal of Contaminant Hydrology*, #16 (1994), pp 109-130.

Characterization and Remediation in Fractured Rocks. Online publication: <https://fracturedrx-1.itrcweb.org/> ITRC, 2017.

Neuman, S. P., 2005. Trends, Prospects And Challenges In Quantifying Flow And Transport Through Fractured Rocks. *Hydrogeology Journal*, March 2005, Volume 13, Issue 1, pp 124–147.

Item 9. Groundwater Data

Groundwater flow and contaminant migration pathways beneath the Red Hill facility are poorly understood. Analysis of groundwater chemistry data can help constrain flow paths. The interim and final groundwater flow models should present reasonable correspondence with available water level and gradient data, so they can underpin the transport model (developed to predict the fate of contaminants from potential releases) which in turn should present reasonable correspondence with available water quality data. This includes contaminant data and other data that may evidence groundwater impacts (e.g., terminal electron acceptors [TEAs]), or of migration directions and mixing of water from different sources (e.g., isotopic data and other quality indicators).

Interpretations of water quality data presented in the CSM Report and GPEC Report are in places non-conservative, and conflict with other lines of evidence and with conclusions reached by regulator SMEs. Example 1: The Navy consultants dismiss some detected results out of concerns for data quality (CSM Report Section 7.2 and Appendix B.7). Though in some instances justified, these concerns do not address all detected results, and from the regulatory perspective, any reported detections that are not qualified are evidence of impacts. Example 2: Independent analyses of TEA data presented and discussed in CSM Report Section 7.3.2 and Appendix B.4 and GPEC Report Figure 6.3 as indications of natural attenuation (e.g., Inset Figure 9.1), dissolved phase contaminant detection frequency and distribution (inset Figure 9.2), and hydraulic gradients, suggest transport occurred not just to the southwest but also to the northwest and possibly northeast of the facility. Example 3: The distribution and concentrations of general chemistry data (i.e. major ions, specific conductivity, and pH) show a poorly-mixed system inconsistent with the Navy CSM of robust flow from upslope recharge areas to Red Hill Shaft. The chemistry is highly variable with chloride concentrations spanning over an order of magnitude and is more suggestive of sluggish down-slope flow and compartmentalization (inset Figures 9.3 and 9.4).

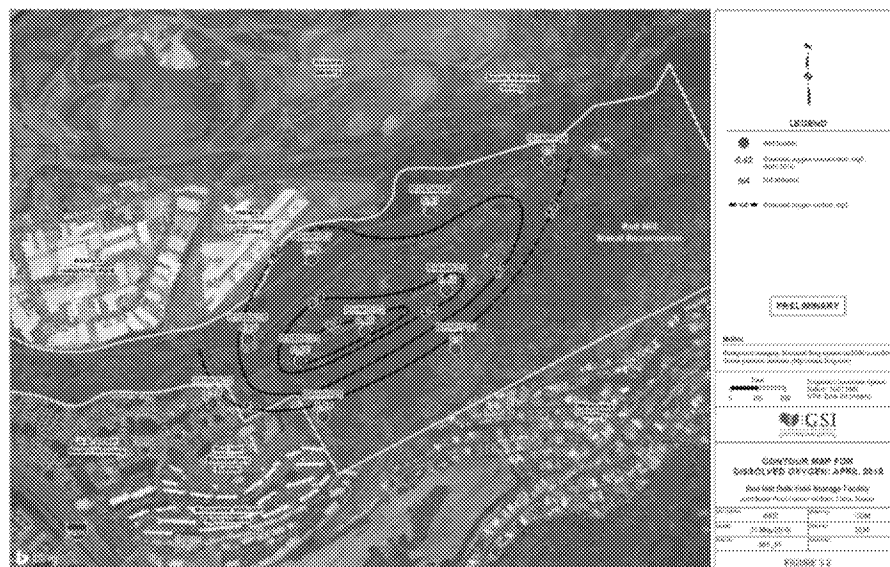


Figure 9.1 Example Terminal Electron Acceptor (TEA) Map – Dissolved Oxygen

The relative absence of high-concentration detections within the small, widely-spaced, monitoring network around Red Hill is not proof of absence of impacts, but appears to be interpreted as such by the Navy consultants. Other data, including TEAs, TPH and individual fuel constituents suggest a broad area of impacts extending in various directions within a complex groundwater flow system that is not uniformly Mauka-to-Makai, with the possibility of LNAPL impacts at the water table as the cause.

Before developing the transport model, it is important that the CSM encompass reasonable interpretations of available water quality data. The CSM should, at this stage, allow for “alternative hypotheses” of at least equivalent likelihood of LNAPL impact to groundwater versus the current hypothesis of there having been no impacts. The final groundwater flow model, when it reasonably represents hydraulic gradient directions and magnitudes in the vicinity of Red Hill ridge, would be anticipated to underpin a contaminant transport model that demonstrates a reasonable match historical sample results (contaminants and TEAs, etc.), thereby demonstrating that the model is useful for near-field transport to understand the available groundwater data, and for developing predictions of contaminant transport and fate to help evaluate risk and mitigating responses or strategies.



Figure 9.2 Example Map of TPH-D Detections

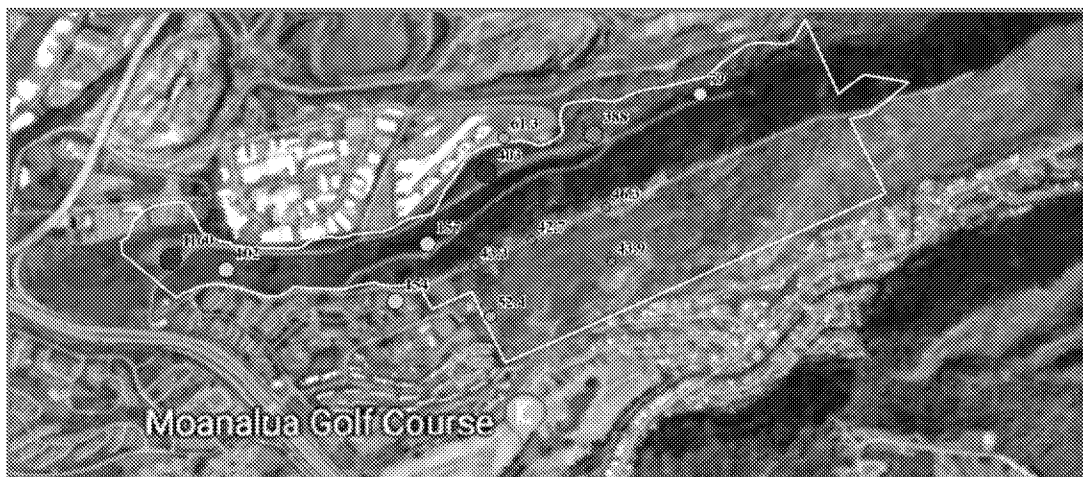


Figure 9.3 Image of Chloride Concentrations Sampled at Wells

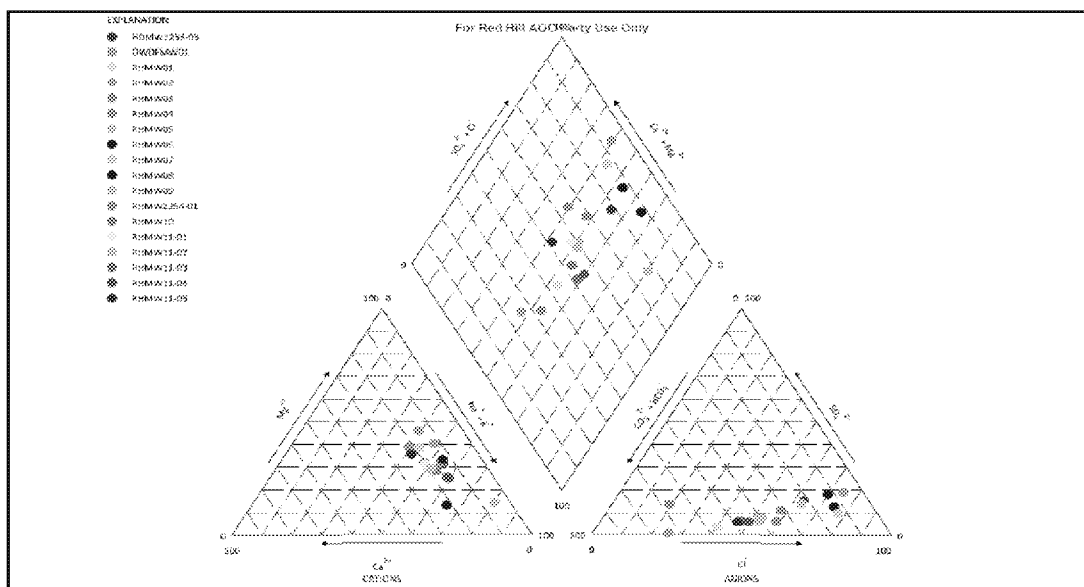


Figure 9.4 Example Piper Diagram

References:

Conceptual Site Model, Investigation and Remediation of Releases and Groundwater Protection and Evaluation, Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "CSM Report")

Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "GPEC Report")

ITEM 10. LNAPL and Dissolved-Phase Plume Distribution.

The LNAPL and dissolved-phase plumes are potentially more widespread than the Navy team's CSM suggests. This has direct implications to the estimation of potential risks and the conservatism therein. The CSM will benefit by consideration of these observations as potentially representative and then accommodate those implications through more thorough evaluations and possibly additional data collection/demonstration.

Site specifically, there are multiple data sets that indicate there has been historic plume movement to the west and northwest and the CSM evaluations do not appear to embrace these observations. For example, the dissolved-oxygen depletion shown in Figure 9.1 closely parallels the observed historic detections of TPHd in groundwater, as expected based on the mechanisms of degradation and transport. The CoC distribution, elevated temperature distribution (Figure 10.1), and other natural attenuation parameters support this plume distribution. While individual data points might be qualified, the data set indicates an ovoid plume elongated along Red Hill Ridge and propagating to the west and northwest as shown in the referenced data in the Navy CSM and selectively herein.

Much less is known with respect to the potential LNAPL distribution in the subsurface that is the source of these groundwater impacts. Simplified transport estimates suggest that for a wide range of general site parametric conditions, the expected downgradient extent of these compounds is typically less than 100-ft away from the LNAPL source feeding the dissolved-phase impacts (Figure 10.2 below).

Naphthenic compounds, due to their chemical properties, are not highly transportable in aquifers. This suggests the possibility of distal LNAPL impacts relative to the Tank Farm from whatever combined historic release have left their signature in the groundwater system (also consistent with attenuation parameters). Naphthenic compounds are frequently detected at several outlying monitoring locations at low concentrations (commonly J-flagged), but the patterns of analyte detections are relatively consistent.

The CSM and the underlying available data cannot (at present) reliably place the LNAPL source zone(s) in context with the observed groundwater plume distribution. The underlying cause for this gap is the absence of source zone characterization in the vertical and lateral dimensions around the Tank Farm, and while recognizing there are practical reasons for this gap, it exists nonetheless. The LNAPL indications in historic angled-core sampling beneath various Red Hill USTs are useful, but none of those investigatory locations were sampled to groundwater. Further, it is unclear whether wells RHMW01 through RHMW03 are directly within the existing LNAPL source zone(s) or not. At the time of their installation there were no gross indications of vadose zone fuel impacts (logs attached in the Appendix), but groundwater was impacted, suggesting a complex relationship between release transport pathways and groundwater impacts. In other words, LNAPL impacts in the vadose and water table regions sourcing these impacts are not delineated by the available investigatory locations. This uncertainty affects the related F&T discussions and framing in the CSM as discussed further below.

The in situ vapor probe response around Tank 5 in the timeframe following the 2014 release suggests that the primary LNAPL migration was to the northwest side of that tank and not in the direction of

RHMW02 (see Figure X.3 below). Actual transport outcomes beneath Tank 5 in 2014 below the vapor probes is unknown; the conservative assumption based on this limited data is that transport was potentially to the northwest and is not represented with any certainty by the spatially limited monitoring well array.



Figure 10.1 Net average temperature greater than the Red Hill Shaft (RHMW2254-01; in degrees Celsius). Like other MNA-related parameters, the elevated temperatures are generally along the Red Hill Ridge and to the west and north. RHMW11 is a newer location and it is unclear why its temperature is elevated. Data source: USGS Synoptic Data, 2018.

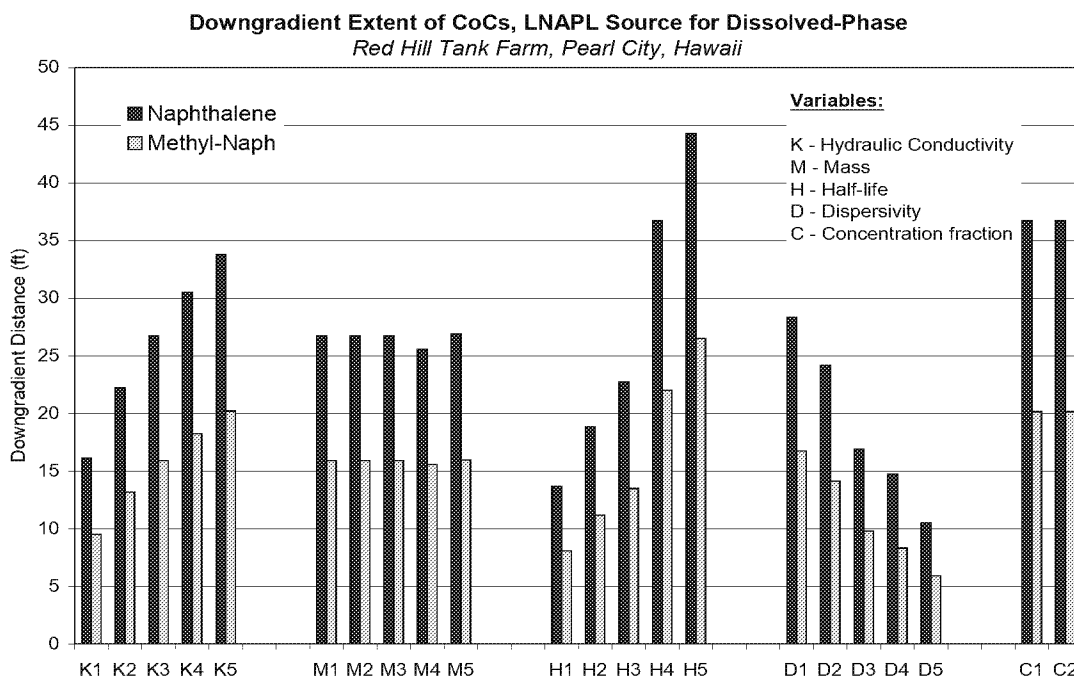


Figure 10.2 Estimated downgradient extent at general lab detection concentrations for naphthalene and methyl-naphthalene under a wide range of transport conditions. Inputs are based on available site area data, the groundwater model, and other local references. The estimate method follows those described by Huntley & Beckett, 2002 (API #4715, 2002).

In terms of the depth of migration of LNAPL from the Tank 5 release in 2014, the primary analysis relied upon in the CSM is the thermal profile at RHMW02, with backup support from chemistry considerations. A net positive temperature profile indicates the effects of exothermic biologic reactions and is affected by a variety of subsurface factors. In general, that relationship can be useful to infer lateral distributions of LNAPL biodegradation (e.g., Figure X.2 above) but is highly uncertain with respect to the LNAPL vertical distribution. In many cases, as shown in the example thermal profile in our August 15, 2018 presentation (Slide 28), the LNAPL vertical mass distribution cannot be inferred from the temperature profile. We believe the Navy technical team needs to validate its interpretation of LNAPL transport around Tank 5 from the 2014 release, as it is a fundamental cornerstone to the remainder of the LNAPL F&T considerations. At a minimum, this would include several Hawai'i or equivalent case examples where the LNAPL source distribution has been definitively interpreted by this method and independently validated through subsurface data demonstrating that actual LNAPL source distribution (e.g., soil cores, LIF investigation, etc.). Alternatively and preferred would be a site specific data collection program to verify the LNAPL source distribution around Tank 5 and possibly other key locations. If that were to be initiated, those first borings should be located to the northwest of Tank 5 where vapor data suggest the potential direction of LNAPL migration occurred.

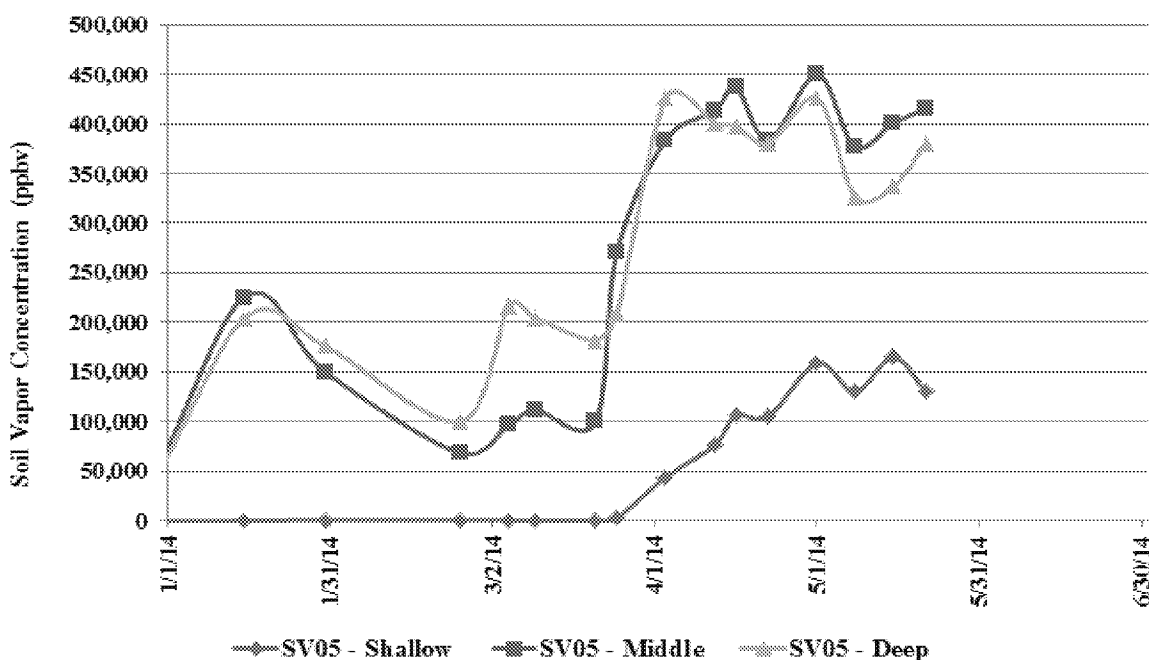


Figure 10.3 Soil vapor probe readings beneath Tank 5 following the January 2014 release. The deep probe is toward the outside of the tank corridor and the shallow probe closest to the tunnel. These data indicate initial release migration was to the northwest of this Tank; note the shallow probe has low level detections that are not visible on a linear plot.

Lastly, CoC concentrations in groundwater at RHMW02 (and occasionally other locations) have often been within the expected solubility ranges for jet, diesel and other fuels stored at the facility, suggesting that LNAPL is likely in direct contact with the aquifer system somewhere in the vicinity. Robert Whittier of the DOH has visually observed LNAPL sheens at RHMW02 in the past, consistent with the solubility range concentrations. In particular, there was a distinct increase in several CoCs at this location immediately following the 2014 release that can be interpreted as a breakthrough curve (Figure X.4). While the Navy team's interpretation is of simple coincident data scatter, these data could also conservatively be interpreted as a new arrival of LNAPL to groundwater in the general vicinity of that well in the timeframe associated with that release. This alternate interpretation of LNAPL reaching the groundwater table following the 2014 release is consistent with site data and transport processes. The CSM would benefit by including this potential as one of the viable working hypotheses, as it is certainly the conservative assumption within this spatially sparse data set. The chemical analyte ratio methods used to suggest otherwise in the CSM are unbounded by site specific data of fuel compositional variability and analyte transformations. Further, we believe where chemical ratios use TPHd values, those should be the native totals and not the silica gel cleaned results because the parent hydrocarbons are predominantly derived from the original petroleum source(s) (whether polar or not as daughter products).

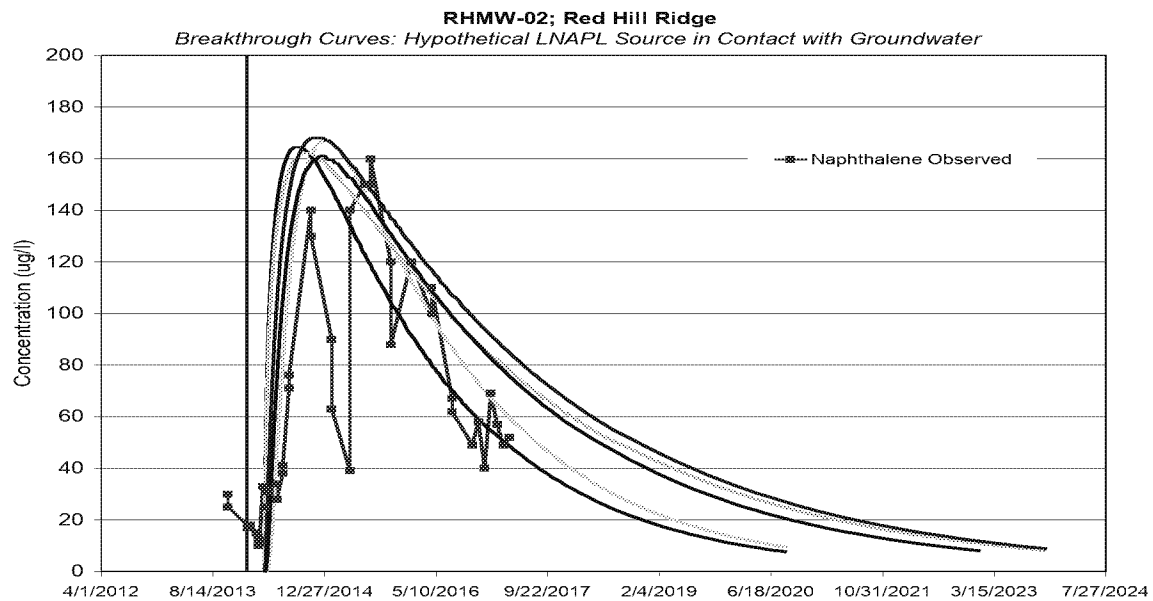


Figure 10.4 Observed naphthalene concentrations following the 2014 Tank 5 release and a family of conceptual contaminant transport breakthrough curves matching those data. Other interpretations are viable, as is the possibility of LNAPL contacting groundwater near RHMW02 following that release.

Attachment 3 - Appendix

ATTACHMENT 4

Presentation Slides from August, 2018

Comments on TUA Deliverables Red Hill Bulk Fuel Storage Are Oahu, Hawaii

Prepared for GWMG Meeting by:

Gary Beckett, Aquiver	Donald Thomas, SOEST
Matthew Tonkin, SSP&A	Robert Whittier, DOH

August 14, 2018

9/11/2018

1

Overview

- Review summary
- Top ten (10) technical comments on TUA reports:
 - Ranked in consideration of priority, likely ease of reconciliation
 - Basis of difference identified
 - Basis of need to resolve comment
- Proposed path forward:
 - Anticipated approach and effort to resolve comment
- Discussion and illustration slides on each comment

9/11/2018

2

Review Summary

9/11/2018

Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility

- Organized deliverable reflecting the work presented previously
- Able to execute most sets of model files with minimal differences from received outputs (version check)
- Model provides foundation for final deliverables, with some refinements recommended here
- Presented path-line results are properly cast as “frequencies” or perhaps sensitivities, not probabilities due to lack of $p(\text{prior})$
 - Some caution also needed on variable grids

9/11/2018

4

Conceptual Site Model, Investigation and Remediation of Releases and Groundwater Protection and Evaluation

- Large volume of high-quality data has been collected that was not previously available to characterize the site
- A great deal learned over the last 18-24 months from these data
- CSM report provides comprehensive documentation of most features and processes at the site, and much of the supporting data
- Some data that are used to support some conclusions don't seem to be presented clearly or comprehensively
- Some assumptions in the CSM may lead to difficulty simulating measured gradients and flowpaths

9/11/2018

5

Top Ten Comments

9/11/2018

6

Comment	Interpretive Difference	Basis of Need
1. Basalt strike-and-dip	• Direction and magnitude in question	• Flow paths, transport
2. Saprolite extents	• Modeled and measured depths up/down valley	• Flow paths, transport, calibration
3. Cap rock, tuffs, sediments	• Feature in CSM but not in interim model	• Flow paths, transport, calibration
4. Preferential pathways	• Incorporation / consideration unclear	• Flow paths, transport
5. Tunnel inflows	• Data reflecting heterogeneity	• Model corroboration
6. Calibration – heads, gradients	• Near-field directions and magnitudes	• Model corroboration
7. LNAPL F&T – vapor data	• Rapid heterogeneous transport vs CSM	• Predictive fate, transport
8. LNAPL F&T – temperature	• Temperature data do not constrain extent	• LNAPL fate, basalt's capacity
9. Groundwater data	• Some data contradict CSM and flow paths	• Fate-and-transport
10. Coastal marine discharge	• Chosen boundary conditions may reduce model sensitivity to parameter changes	• Predictive reliability

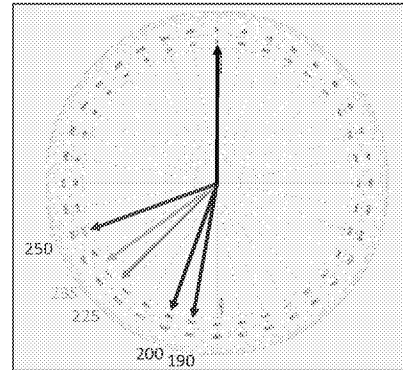
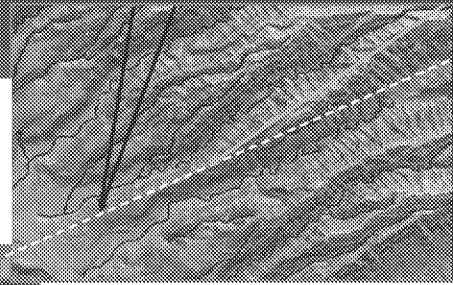
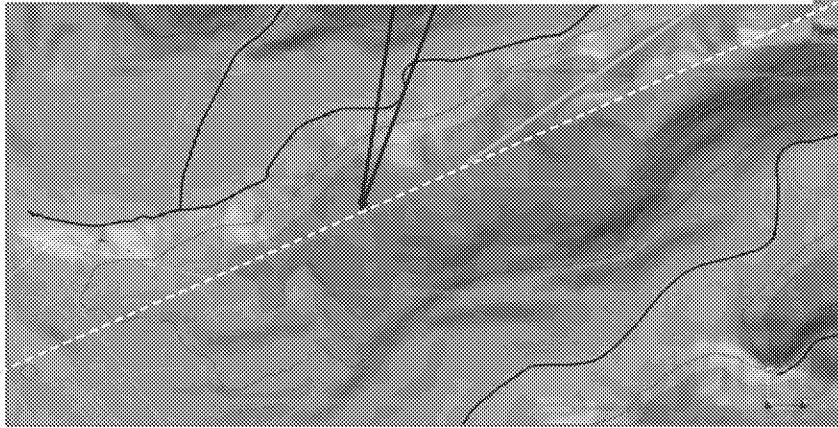
Path Forward

Comment	Proposed Path Forward	Data Gap	Effort
1. Basalt strike-and-dip	<ul style="list-style-type: none"> • Collaborative SME review of available dip & strike data <ul style="list-style-type: none"> • Corresponding “base” model update 	Unlikely	Moderate
2. Saprolite extents	<ul style="list-style-type: none"> • Collaborative SME review of geophysics and CSM <ul style="list-style-type: none"> • Targeted seismic ground-truthing • Corresponding “base” model update 	Unlikely	Moderate
3. Cap rock, tuffs, sediments	<ul style="list-style-type: none"> • Collaborative SME review of CSM <ul style="list-style-type: none"> • Corresponding “base” model update 	Partially	Small
4. Preferential pathways	<ul style="list-style-type: none"> • Suitable acknowledgement • Collaborative SME plan for representation in final F&T models 	Yes*	Small
5. Tunnel inflows	<ul style="list-style-type: none"> • Model testing with predictive sensitivity analysis 	Unlikely	Small
6. Calibration – heads, gradients	<ul style="list-style-type: none"> • Review of calibration following CSM revisions if made 	Partially	Moderate
7. LNAPL F&T – vapor data	<ul style="list-style-type: none"> • Evaluation in context of 2014 and earlier releases • Constituent-specific sampling vs PID (release detection) <ul style="list-style-type: none"> • Suitable acknowledgement 	Unlikely	Moderate
8. LNAPL F&T – temperature	<ul style="list-style-type: none"> • Evaluation of plausible alternative interpretations 	Partially	Small
9. Groundwater data	<ul style="list-style-type: none"> • Comprehensive tabulation of COC data with qualifiers <ul style="list-style-type: none"> • Expanded interpretative analysis of NAP/TEA 	Yes	Moderate
10. Coastal marine discharge	<ul style="list-style-type: none"> • Collaborative SME review of available boundary conditions 	Partially	Moderate

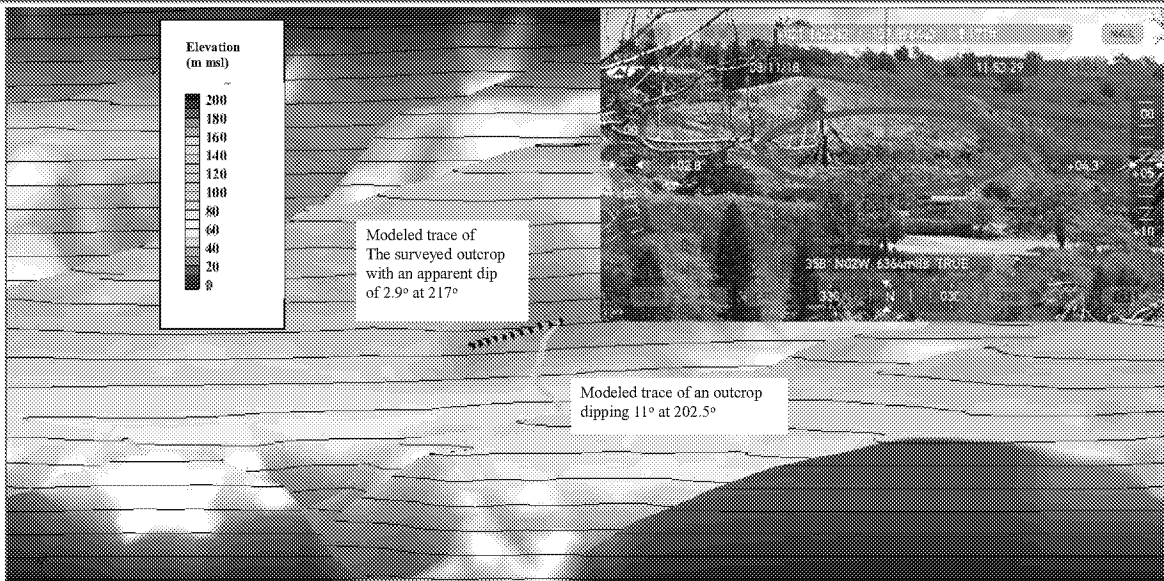
Discussion of Comments

1. Strike and Dip

- Geo-statistics "maximum"
- Local Red Hill ridge alignment (topographic)
- Geo-statistics "typical" (similar to regional Red Hill ridge alignment)
- Geo-statistics "minimum"
- Proposed in TUA CSM

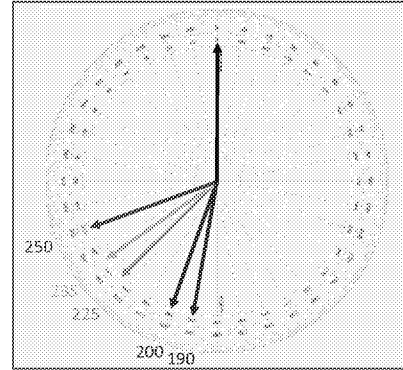
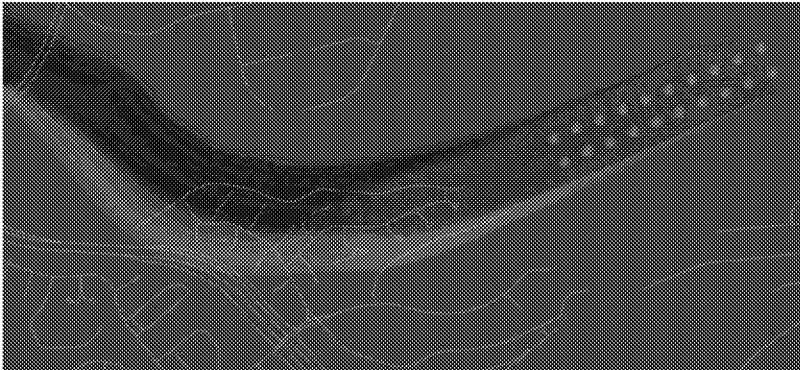


1. Strike and Dip



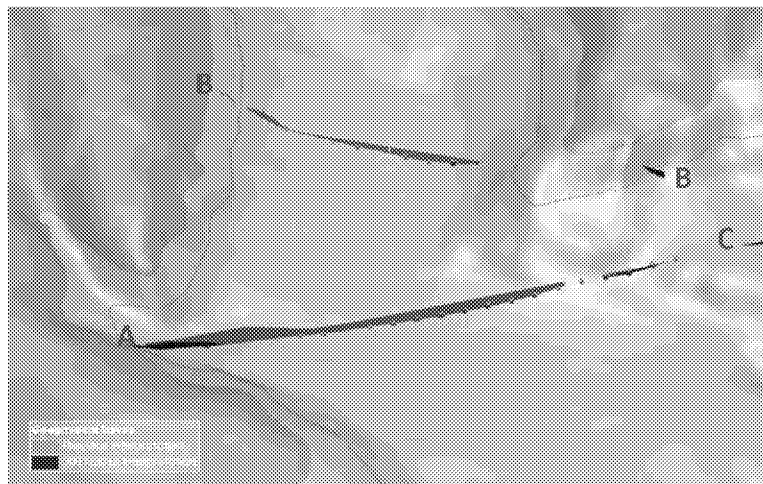
1. Strike and Dip

- Rudimentary tests - paths sensitive to assumed direction, magnitude
- Thorough testing or sensitivity analysis requires grid-realignment or full conductance tensor



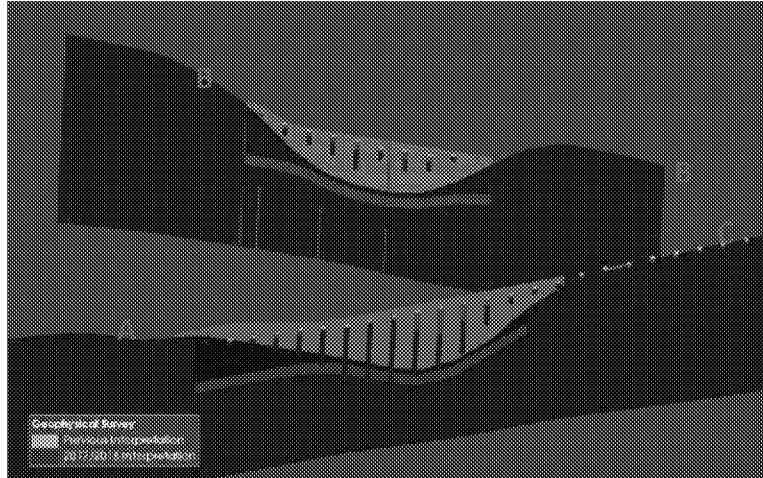
2. Saprolite Extents

- "Key reflectors include the base of alluvium or top of saprolite, top of water saturated (possibly perched) sediments, and the contact between weathered basalt (saprolite) and unweathered basalt.
- Valley fill sediments are constrained to the upper 60 ft below land surface in all three valleys.
- Saturated and/or competent saprolite are mapped from surface to hundreds of feet bgs."



2. Saprolite Extents

- Valley alluvium thickness
- Systematic pattern of modeled saprolite depth
- Early termination of longitudinal extents of saprolite
- Layer elevations based on prior interpretations may require revision to accurately represent conditions



9/11/2018

15

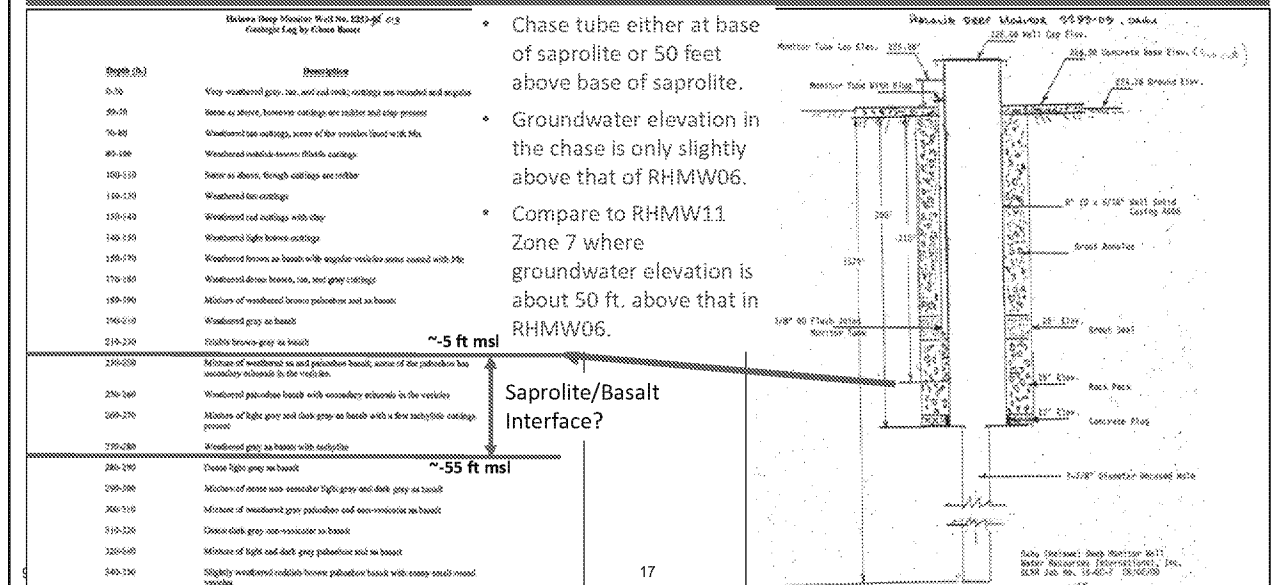
2. Saprolite Extents

- HDMW2253-03 as Ground-truth
 - Can we definitively define the saprolite/basalt interface from available data?
 - Geo-logs
 - Well construction
 - Water level in the HDMW Chase Tube
 - Groundwater elevation vs. RHMW11 Zone 7

9/11/2018

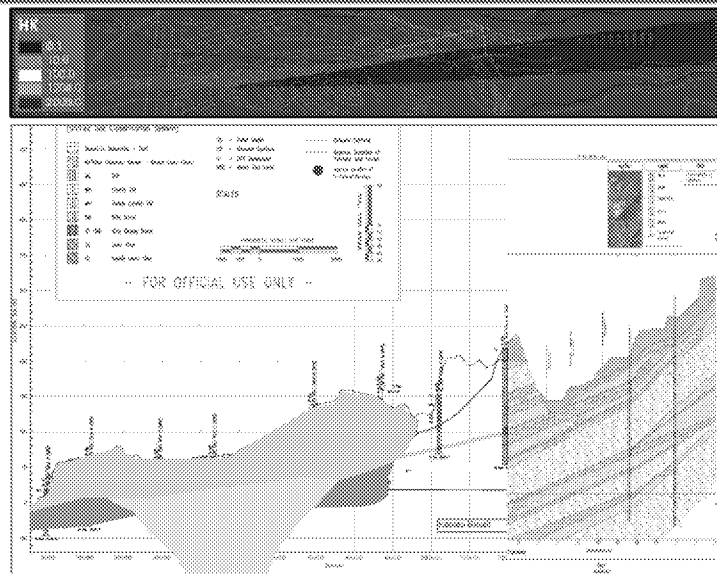
16

2. Saprolite Extents

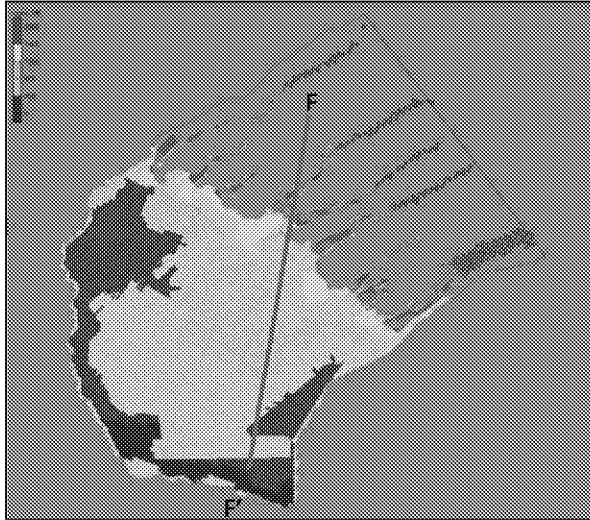


3. Cap Rock, Tuffs, Sediments

- Documented presence of tuffs and low-conductivity sediments
- Valley saprolites may "key-in" to these lower-conductivity sediments
- Resulting hydro-stratigraphic system may alter flow patterns as far up as Red Hill



3. Cap Rock, Tuffs, Sediments



- Model appears to lack the confining nature of older alluvium.
- Expect bulk hydraulic conductivity of the caprock to be $\ll 1,000$ ft/d

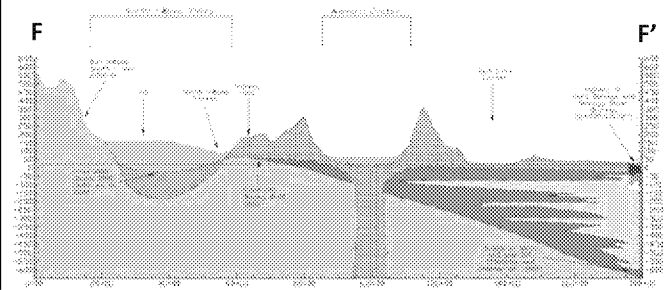
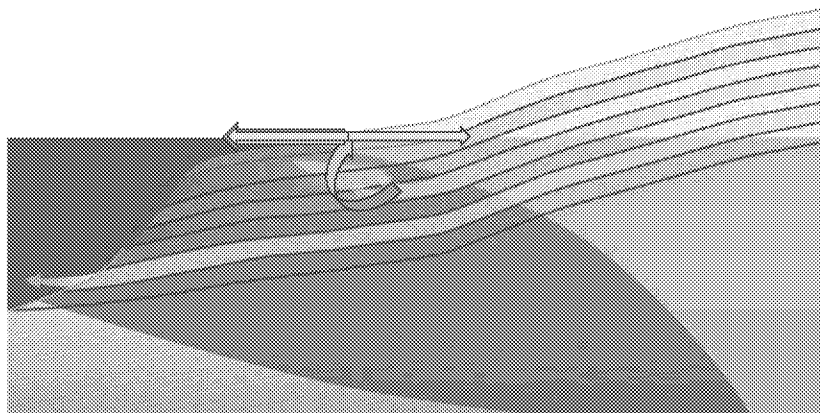


Figure 5-9 CSM

9/11/2018

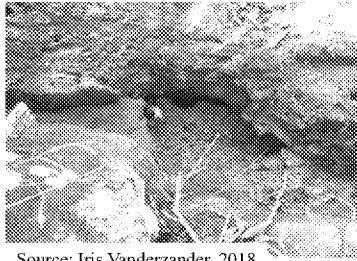
19

3. Cap Rock, Tuffs, Sediments

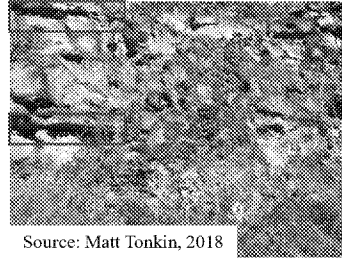


9/11/2018

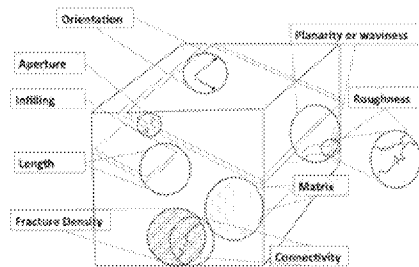
4. Preferential Pathways



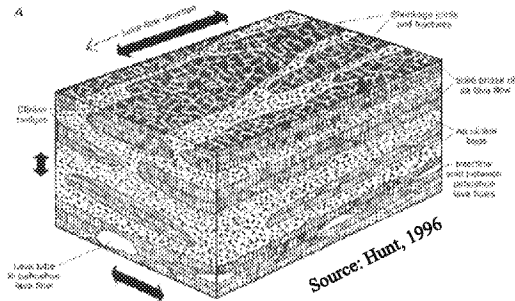
Source: Iris Vanderzander, 2018



Source: Matt Tonkin, 2018



Source: ITRC, 2017



Source: Hunt, 1996

9/11/2018

21

4. Preferential Pathways

- Thirteen of twenty tank barrel-log sets intercepted at least one lava tube:
 - Other areas of broken rock may represent collapsed lava tubes
- Connectivity, role in flow and transport, are uncertain

Table 6-2: RHMW11 Hydraulic Conductivity Estimates Derived from Pneumatic Testing and Laboratory Analyses

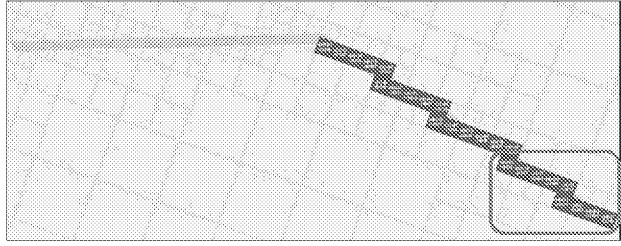
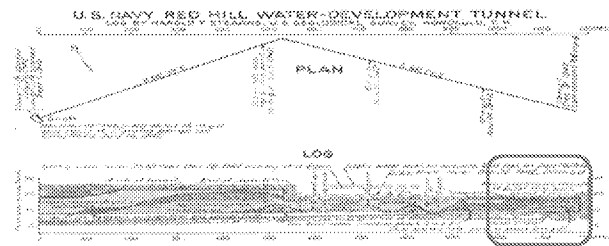
Slug Test Zone	K (Hvorslev 1951)		K (Bouwer & Rice 1976)		K (Cooper et al. 1967)		Date	Zone Geology / Feature
	ft/d	cm/sec	ft/d	cm/sec	ft/d	cm/sec		
Zone 8	9.2E-02	9.3E-05	1.0E-01	9.5E-05	7.1E-02	2.5E-05	12/13/2017	Saprolite
Zone 7	1.2E-01	4.2E-05	1.3E-01	4.6E-05	1.1E-01	3.8E-05	12/8/2017	Saprolite, clinker zone
Zone 7	2.6E-01	9.2E-05	2.8E-01	9.9E-05	2.7E-01	9.7E-05	12/11/2017	Saprolite, clinker zone
Zone 5	3.4E-01	1.2E-04	2.9E-01	9.9E-05	1.7E-01	6.0E-05	12/7/2017	Saprolite
Zone 5	---	---	---	---	---	---	---	Lava tube
Zone 4	---	---	---	---	---	---	---	Pāhoehoe
Zone 3	---	---	---	---	---	---	---	Pāhoehoe
Zone 2	---	---	---	---	---	---	---	Clinker zone
Zone 1	---	---	---	---	---	---	---	Clinker zone



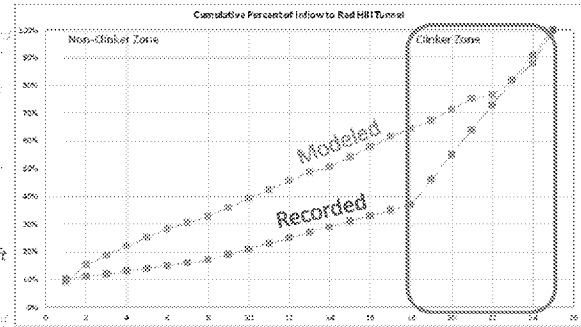
9/11/2018

22

5. Tunnel Inflows

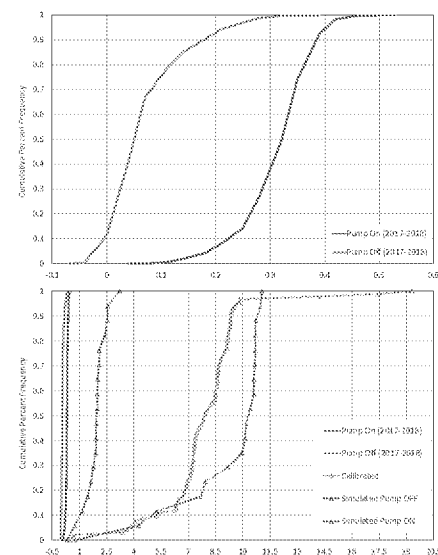
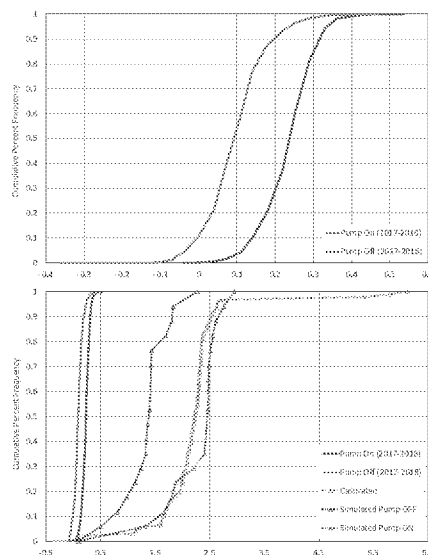


"The heterogeneous nature of the clinker is revealed in the geologic log at the Red Hill Shaft-water development tunnel prepared by the USGS (Stearns, 1943). That log, reproduced as Figure 5-10, reveals that water inflows were measured by the USGS as the tunnel was being constructed. The log shows that flow rates dramatically increased as the tunnel penetrated beyond 550 ft, which is attributable to a large increase in permeability at the basal location, the Figure 5-10, and relatively thin 'clinker' logged in the first 150 ft of the tunnel's water lift produced essentially no groundwater. The tunnel was described as 'dry' during tunneling out to about 480 ft from the shaft. Subsequent thinning of this section, but often even sand pits, produced about 1.5 mgd. Progressing beyond 480 ft, the tunnel produced greater water inflows. At 700 ft the rate was estimated to be 5 mgd. After working 180 ft, the flow rate had risen to 12 mgd. From that point forward, the rate of inflow increased as the tunnel progressed much faster. In the last 200 ft of the tunnel, 980–1,180 ft from the shaft, the groundwater inflows increased from 12 mgd to 29 mgd. The thicker clinker zone shown on the geologic log (Stearns 1943) produced the majority of the groundwater. This 200-ft clinker produced about 8 times more water than the clinker and pāhoehoe logged in the initial 480 ft of the tunnel. In summary, by the end of the Red Hill water development tunneling project, the groundwater inflow from the tunnel had increased from approximately 5 mgd to 29 mgd in the last 500 ft of



6. Calibration – Heads, Gradients

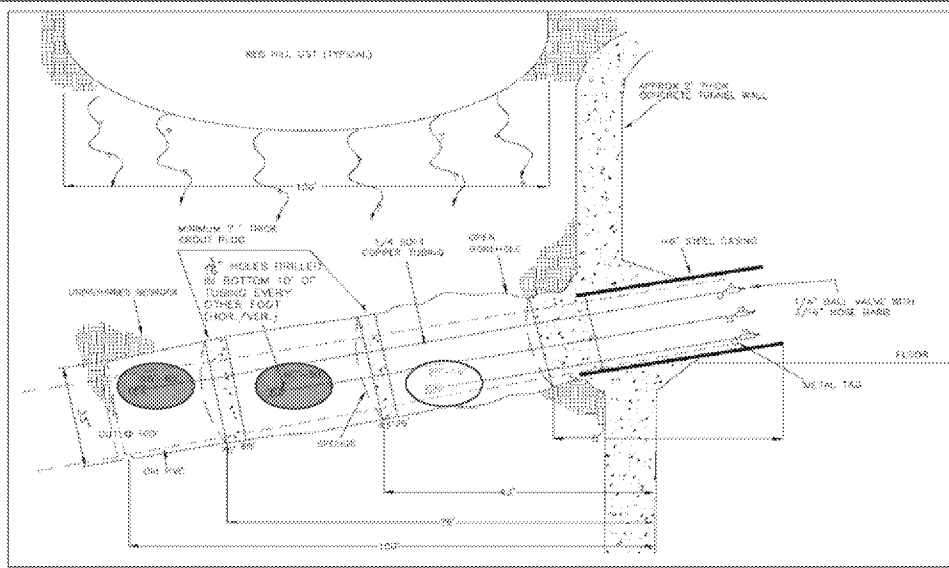
- Historic manual data infrequent, irregular
- Synoptic data improve CSM
 - Time-weighting
- Absolute head vs. gradients
- Systematic difference



9/11/2018

7. LNAPL F&T - Vapor Data

- Schematic of general vapor probe layout
- Angle boring, with deepest vapor port furthest from tunnel

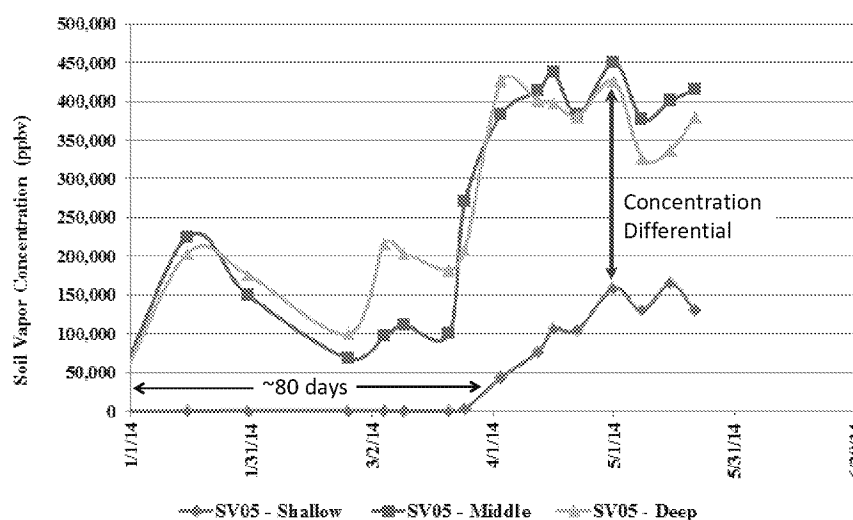


9/11/2018

Source: EON (2007), Figure 2.2

7. LNAPL F&T - Vapor Data

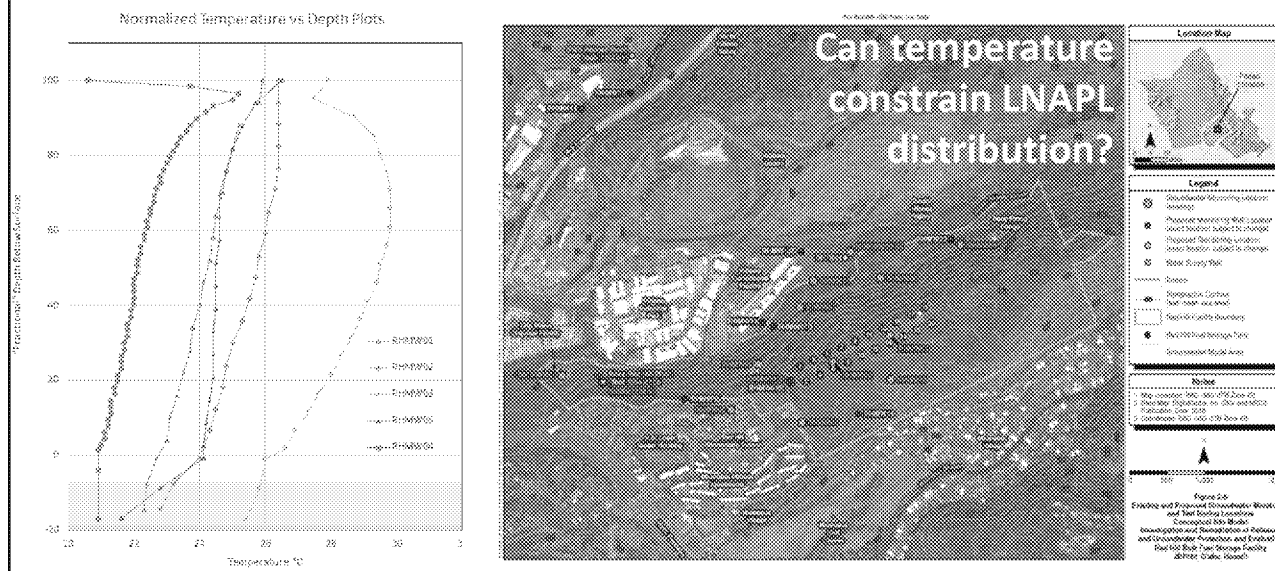
- RHMW05 vapor behavior following 2014 release
- Shallow (interior) port slowest to respond, and response damped



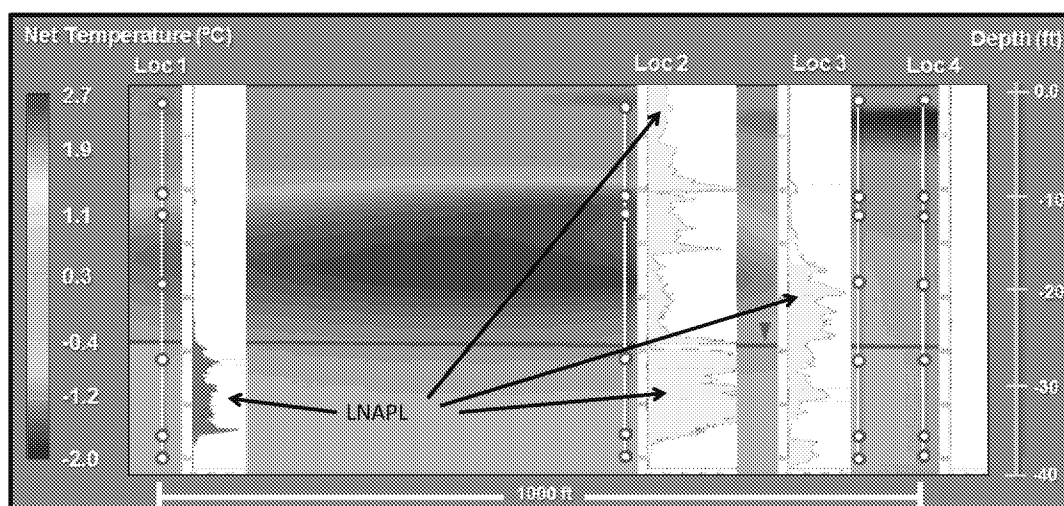
9/11/2018

26

8. LNAPL F&T – Temperature



8. LNAPL F&T – Temperature

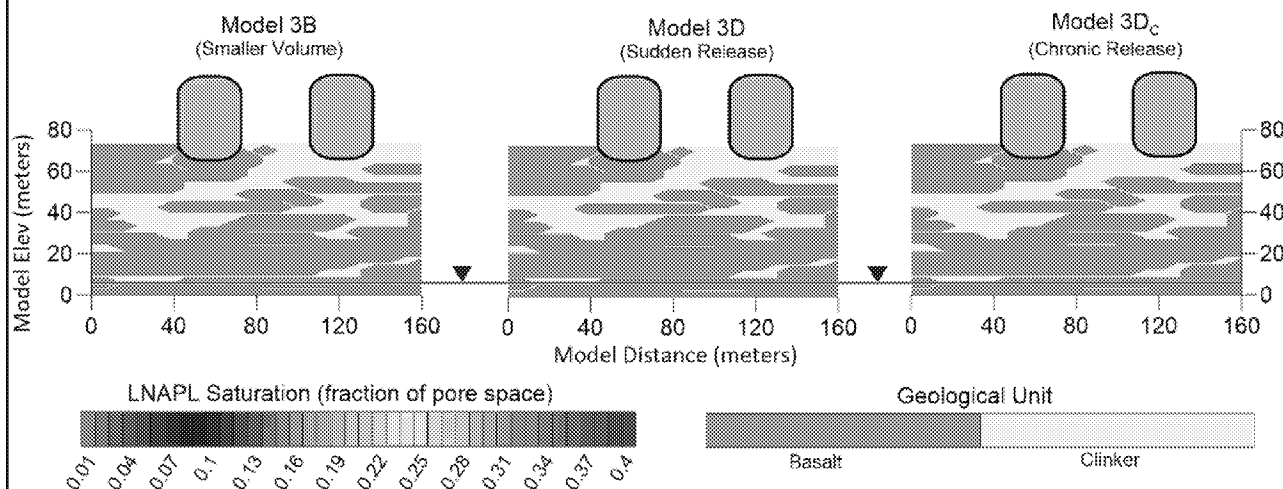


after Stockwell, E., 2015. Colorado State University.

8. LNAPL F&T – Example Animations

LNAPL HYPOTHETICAL TANK RELEASE

Simulation Time: 1 Minutes



9. Groundwater Data

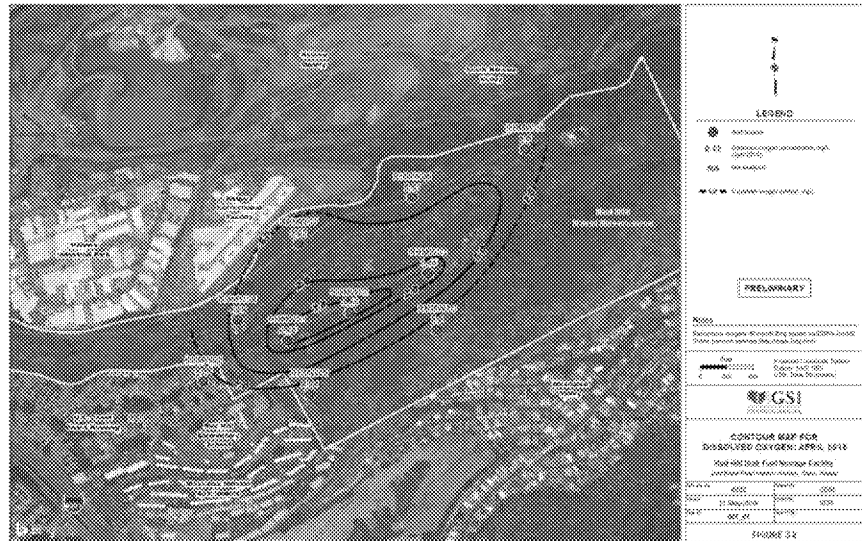
Distal
detections
at of TPH
(even
recognizing
some data
should be
qualified)



9/11/2018

9. Groundwater Data

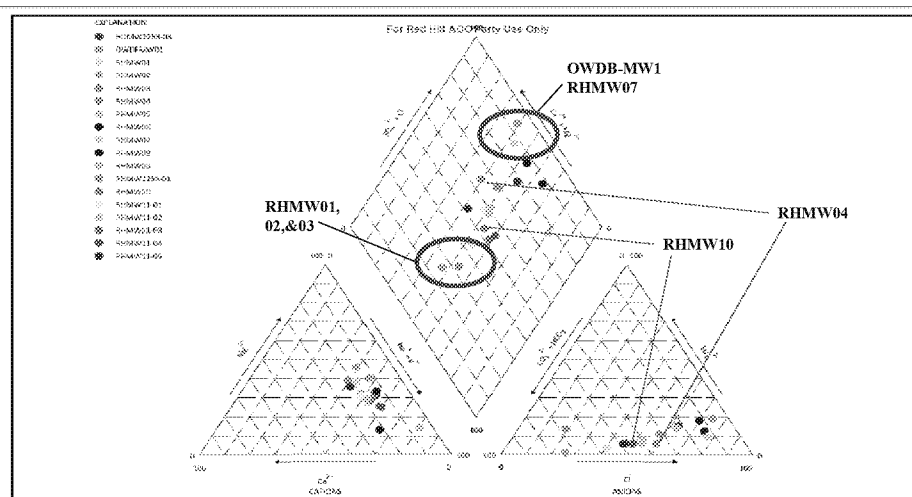
- Natural attenuation parameters describe a plume shadow:
- Example shown is depleted O_2



9/11/2018

Figure 3-2: Contour Plot of O_2 Concentrations from the Facility Groundwater Monitoring Network (April 23-25, 2018)

9. Groundwater Data



- Does the chemistry data show a flow path?
 - A potential mixing lines exists
 - However problems with spatial distribution
 - Possible more indicative of waters with contrasting chemistry

9/11/2018

32

9. Groundwater Data



Chemistry shows indication of a poorly mixed system

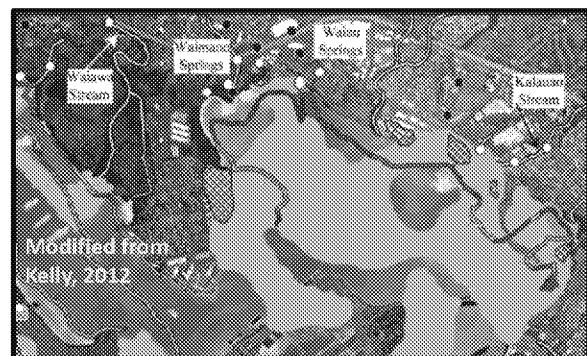
- Chloride conc. vary from ~40- >1000 mg/L
- Southeast very different from northwest
- Northwest chlorides still highly variable
- A large flux of groundwater down the Red Hill ridge should show better mixing

9/11/2018

33

10. Coastal/Submarine Discharge

- Combination of high caprock K, GHB, and Pearl Harbor Embayment
- Likely results in model directing GW Flow into NE Pearl Harbor



- Temperature (cooler colors indicate GW Flow) and
- Radon lines (red indicates GW Flow)
- Indicate little GW discharge into NE Pearl Harbor.